# PROPERTIES AND STABILITY OF A TEXAS BARRIER BEACH INLET



Prepared by

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## ABSTRACT

An environmental study was conducted at Brown Cedar Cut, a natural unstable barrier beach inlet connecting East Matagorda Bay, Texas, with the Gulf of Mexico. The objectives of this study were to determine the physical and hydraulic properties of the inlet, and to investigate the inlet's historical stability, as well as its short-term response to a number of physical processes. Results of the study indicate that hurricanes and continuing erosion of adjacent beaches enhance the long-term stability of the inlet. During winter months, the rapid passage of strong frontal systems and associated winds, as well as substantial amounts of rainfall, are primarily responsible for the day-to-day viability of the channel boundaries. In the absence of such forces, the predominance of littoral drift over the limited flushing ability of astronomical tidal currents leads to degradation of the inlet channel and westward migration of the entire inlet system.

# PREFACE

Research described in this report was conducted as part of the continuing research program in Coastal Engineering and Oceanography at Texas A&M University.

This report was primarily written by the senior author in fulfillment of the thesis requirement for a Master of Science Degree in Oceanography under the supervision of the junior author, who acted as major advisor.

The review of this report by Dr. Takashi Ichiye and Dr. William R. Bryant is very much appreciated. Special thanks are extended to those perserverent individuals who volunteered in assisting in the field surveys: Pierce Chandler, Charlie Chesnut, Brian Eadie, Brady Elliot, Duncan Fitzgerald, Lynn Hales, Jim Hampton, Lars Joshson, Doug Martin, Mike McClenan, George Owens, Harold Prather, Dr. Robert Schiller, and especially to Chuck Kindel for his unfailing assistance and companionship. Recognition should also be given to Robert Taylor, Paul Kruckmeyer, and Bill Opfel for their help in analyzing and preparing the data for publication.

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# INTRODUCTION

The shorelines of many of the world's continents are characterized by broad expanses of sandy beaches. Those beaches situated on long, narrow islands separated from the mainland by substantial regions of water are termed barrier beaches. In general, the only connection between the enclosed bay or lagoon and the ocean is by means of restricted channels through the barrier island. Such channels are referred to as tidal inlets, since their existence is attributed directly to the currents produced by the rise and fall of the tides. In the absence of tidal action, most inlets would rapidly be filled in by the sand which moves along the coast in response to wave action.

The existence of many of these inlets has varied with time, depending upon the ability of the tidal currents to maintain a channel through the island. When a viable channel does exist, its position may fluctuate drastically in response to the many natural processes acting upon the inlet. Such processes include surface runoff, normal tidal action, wave activity, local wind-generated tides, and extreme conditions of waves and tides produced by the passage of large storms.

At the present time, great expenditures of time and money are being made to artificially maintain navigable channels through barrier island systems. Many times this is achieved by dredging of the main channel to remove sand deposited by wave and current action. Installation of coastal structures which impede the movement of sand into the inlet or which accelerate the flow to allow natural scouring of the channel also may be employed. The maintenance of navigational inlets is of great importance to the operators of commercial vessels who must travel from mainland ports to the open ocean. In addition, exchange of water between bay and ocean is necessary for the continued existence of shallow water organisms which utilize the bays as breeding grounds and nurseries. Inlet closure can effect drastic increases or decreases in the bay water salinity so critical to these animals. Finally, extensive loss of property may result from the uncontrolled migration of an inlet along densely populated beaches.

Over eighty per cent of the Texas coastline is comprised of a barrier beach regime such as that described above. The barrier beaches are interspersed with over a dozen tidal inlets, ranging in width from a few hundred feet to almost one mile. In general, the study of physical processes affecting the inlets has been quite limited. Little detailed environmental data are available which may be correlated with short-term shoreline changes. Therefore, a study was undertaken to investigate the environmental characteristics of a small Texas barrier beach inlet, with the hope of being able to clearly define the nature and magnitude of those processes controlling its behavior.

The objectives of the investigation were fourfold: First, to determine the hydraulic and geologic characteristics of a natural barrier beach inlet. Second, to identify and establish the relative importance of those natural processes influencing the character and properties of the inlet. Third, to determine the stability of the inlet. Finally, to apply theories concerning tidal-induced flow and inlet stability to conditions prevailing at the inlet and to compare the results of such theories with experimentally determined conclusions.

The inlet selected for study was Brown Cedar Cut, which is located on the northeast Texas coast about twenty-five miles south of Freeport, as shown in Figure 1. This inlet was chosen primarily for its small size and because maintenance of the channel is due entirely to natural processes--man's attempts to control it have been minimal. The inlet is the sole direct connection between the Gulf of Mexico and East Matagorda Bay, a shallow estuary some fifty-four square miles in extent. It is one of the more variable inlets on the coast, opening, closing or migrating in response to dominant physical processes. Field investigations of Brown Cedar Cut were conducted from October, 1970, to April, 1971, a period during which the day-to-day processes exhibit their most pronounced

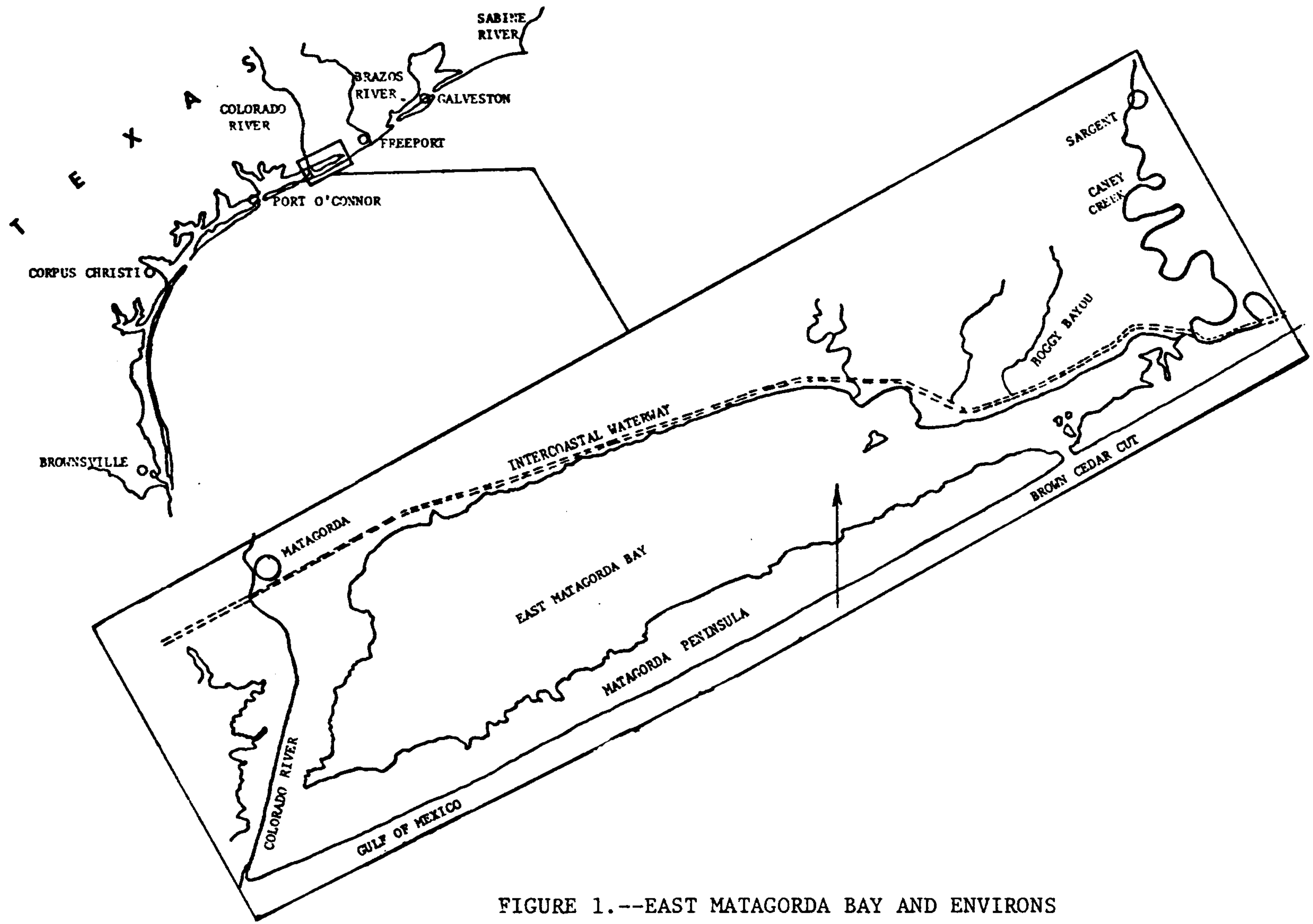



FIGURE 1.--EAST MATAGORDA BAY AND ENVIRONS

variations in character and magnitude. Prior to discussing the results of the study, a general introduction to inlet characteristics will be presented.

## Inlet Formation

It is a well documented fact that tidal inlets owe their continued existence to currents generated by the passage of the tide through their channels. Although complex in scope, qualitative observations of current and sand transport patterns allow comprehensive analysis of maintenance processes. However, formation of many inlets occurs during severe storms and the exact nature of the processes responsible is not clearly understood. In general, three mechanisms of inlet formation are commonly recognized.

Perhaps the most unique method of formation is the growth of a sand spit across the open mouth of a large bay or lagoon. Oblique wave action transports sand along the coast to the bay entrance. In the absence of strong currents, sand is deposited and, with a continuous supply of sand, a spit or bar progresses across the entrance. This process continues until a narrow opening is all that connects the enclosed bay with the ocean. If the bay's tidal prism is sufficiently large, currents developed due to differences between bay and ocean water levels preclude the further growth of the spit, and a tidal inlet is established. Assateague Anchorage, Virginia, was formed in this manner (5).

Man's requirement for ease of navigation and other economic considerations have long been stimuli for the artificial creation of inlets through narrow stretches of shoreline. Dredging, bulldozing, and dynamiting have all been employed to excavate such channels. Once accomplished, however, these actions can produce undesirable side effects. A stable beach, in equilibrium with local processes, may be severely disturbed by the sudden presence of an inlet. The natural longshore transport of sand is interrupted, and if sufficient sand is not provided to the down-coast side of the inlet, erosion of the beach is usually guaranteed. In some instances, the tidal currents produced in an artificial inlet may be so great as to cause severe erosion of the channel banks, with subsequent loss of adjacent property. An example of such a "runaway" inlet was Rollover Pass on the northeast Texas coast. This inlet was first excavated in 1954 and, until protective sheep piling walls were installed, threatened to consume a significant number of houses in its quest for an equilibrium configuration. The most common error made by inlet designers concerns the prediction of current and sand interactions. In many cases, overestimation of the current magnitude combined with an underestimation of the quantity of sand delivered to the inlet mouth has resulted in the closure of artificial inlets. Brown Cedar Cut was once opened by dredging, but reclosed within a week. Based on extensive historical evidence, indiscriminant inlet cutting must not be encouraged. A comprehensive study of all natural processes acting at the proposed location and the effects of an inlet on these processes must be performed prior to construction if additional degradation of the nation's shoreline is to be avoided.

Perhaps the most common method of inlet formation is the natural breakthrough of existing barrier islands. Two possible causes of inlet formation in this manner have been documented, and both are associated with a rise in sea level due to the passage of a large storm.

Johnson (26) attributes inlet formation on a barrier island to the combined action of waves and high water acting from the ocean side. Frontal wave attack on low points in the island causes transport of water into the bay, with subsequent scour of a channel. When water levels return to normal, an inlet is formed which allows continued exchange of water by means of tidal differences. However, Shaler (48) states that inlets are formed when the rise in sea level is much greater in the lagoon than in the ocean. Thus, water flows across low areas in the island from the bay side, and rapidly scours a channel through the island. Pierce, (40) in a review of various formation processes, reasons that only on narrow islands can currents resulting from oceanic wave action be of sufficient magnitude to cause scour of deep channels; on wide islands the loss of velocity due to friction precludes significant scour. However, breakthroughs from the bay side on both wide and narrow islands have been attributed to the gradual buildup of water in the lagoon, followed by a sudden shift in wind to an offshore direction (40). Thus, large quantities of water are piled up on the island and breakthrough occurs in low-lying sections.

Studies of existing inlets and their methods of origin indicate that both the above theories are valid for certain inlets. In some cases, wave action and high bay water levels work together; the ocean waves producing erosion of protective beach dunes followed by scouring due to seaward flowing currents. Wave-cut channels occurred along many sections of the Atlantic coast barrier islands as a result of a large storm in March, 1962 (41). A large inlet formed by the seaward flow of water from behind a barrier island occurred as a result of an August, 1933 storm at Ocean City, Maryland. Bay water levels were much higher than the open ocean levels, and water flowed through the inlet for forty-eight hours after its formation (16).

## Inlet Stability

Inlet stability may be defined as the tendency for an inlet to maintain a permanent position and configuration, that is, geographic and geometric stability. Deviation from geographic stability is termed inlet migration, and may pertain to the lateral movement of the inlet as a whole or to migration of individual channels across the shoal areas at the ends of the inlet. Geometric stability is the maintenance of constant cross-sectional area and shape. In general, the two types of stability are closely linked. Changes in cross-sectional area or shape may result in decreased current velocities and channels could eventually close or migrate due to deposition of sediments. Similarly, if the channel were allowed to migrate and become quite long, then the energy which previously was used to maintain a stable cross-section would be consumed by frictional forces, and closure would again result. The problem of inlet stability will be discussed in detail in later portions of this thesis, and for the present only those factors which significantly affect the stability will be introduced.

It was stated previously that currents produced in tidal inlets result from the rise and fall of the tides. More precisely, such currents are hydraulic in origin, and are defined as

> gravity flows through a channel that results from a difference between water levels at the two ends of the channel because of a difference in phase and/or range of the tide. (2)

The magnitude of these currents depends upon the length of the channel, the difference in water elevation between the sea and lagoon ends of the channel, the size and shape of the cross-section, and the roughness of the channel bottom and sides. For a stable channel to be maintained, the velocities must be such that neither significant scour nor deposition occurs over a tidal cycle. Bruun and Gerritsen (8) liken a stable bed to a "rolling carpet" of alluvial material moving back and forth on the inlet bottom in response to tidal currents. Velocities greater than those required for equilibrium cause loss of the bed material, while insufficient velocities result in an inability to remove sand supplied to the inlet by wave action, with subsequent deposition.

This leads directly to consideration of the quantity of littoral drift being transported along the beaches on the updrift side of the inlet. Upon reaching the inlet environs, some sand may be permanently deposited in and around the inlet. The remainder is bypassed, and continues its migration along the downdrift shoreline. Such bypassing may take place along the offshore bar extending across the mouth of many inlets or within the interior channels, where ebb and flood currents combine to produce a net transverse sand transport. When large quantities of sand are deposited at the inlet mouth, a spit develops and the whole inlet migrates in a downdrift direction. At other times, sand may be deposited along the inlet bottom, and geometric stability will not be maintained. It is the balance between tidal currents and littoral drift which determines the ultimate fate of the channel.

Wave action and surface runoff also effect the stability of an inlet. Some inlets depend upon heavy rainfalls and runoff into the bay to periodically flush out their channels. Wave action impinging perpendicular to the shoreline will not produce the long-shore currents necessary to sustain littoral drift, and the waves themselves may propagate into the channel and cause erosion of the banks.

Determination of the stability of Brown Cedar Cut requires an investigation into the relative importance of these and other physical processes.

# LITERATURE REVIEW

The study of tidal inlets on sandy coasts has been a topic of interest for some time. Johnson (26), in an early work, recognized the importance of wave and current action on the formation and maintenance of these channels. However, Brown's comprehensive paper on detailed characteristics of inlets, presenting as well certain mathematical relationships between tidal fluctuations and current velocities through the channel, marked the first major work on the subject (5). Shortly thereafter, O'Brien discovered a linear relationship between the area of the inlet channel and the tidal prism of the enclosed bay for a number of stable inlets on the Pacific Coast (38). Subsequent investigation of inlets on the Atlantic and Gulf Coasts revealed the widespread applicability of this linear correspondence (39). However, detailed investigations into the nature and importance of the processes affecting inlet stability have been relatively few. The most complete work in this field has been accomplished by Bruun (6) and Bruun and Gerritsen (8) who attempted to assess the importance of various environmental parameters to the problem. The effects of littoral drift on the properties of various inlets have been particularly well documented (7). A comprehensive review of design criteria by Graf (19), reveals that the design of stable channels in alluvial materials has been investigated over a long period of time, and that knowledge of shear stress values required for stability of such channels is fairly well established. However, Bruun's application of selected stream bed stability theories (8) to the large-scale processes involved with natural inlets represented an original approach to the determination of stability criteria.

Detailed knowledge of inlet characteristics on the Texas coast is largely the result of Price (43,44,45) who established the importance of north winds on the stability of many Texas inlets. In addition, characteristic patterns exhibited by the ebb and flood current channels of Texas inlets were reported (47), and are applicable to inlets located on other coasts as well. Some engineering design studies concerning inlets on the Texas coast have been conducted, mostly in connection with plans to alter the extreme salinities of certain Texas bays (20,33,34). Such studies have attempted to predict inlet stability by applying various simplified hydraulic criteria. As yet, the inlets proposed have not been constructed, so empirical evaluation of the methods has not been accomplished. Previous investigation concerning environmental characteristics of Brown Cedar Cut are limited to one set of field data collected in February, 1954 (32).

Throughout many investigations of the stability of tidal inlets, it appears that the single most important factor is the magnitude of currents generated by the passage of the tide through the inlet. Considerable study of the prediction of such currents based on the knowledge of the tidal cycles has been made (1,9,18, 27,30,49). For the purposes of this study, an attempt will be made to utilize an established relationship between the slope of the water surface and the resultant velocity, keeping in mind that simplicity of application is of importance to engineering studies. Computed values will be compared to observed velocities for evaluation of the selected equation.

Finally, mention should be made of progress in the study of coastal processes which affect inlet characteristics. Evans (17), in an investigation of spit-building processes, discovered the importance of wave refraction on the growth of hooked or recurved spits. Yasso (59), in a more detailed study, found that such growth may occur as a result of the landward migration of sand ridges which originate below mean low water in response to wave activity. Refraction of waves was considered recently by Hayes to be the cause of more large-scale, sedimentary phenomena (23).

This literature survey is intended to merely highlight previous work in the study of coastal inlets. Detailed consideration of these and other investigations will be presented in following sections.

# HISTORICAL BACKGROUND

As mentioned previously, Brown Cedar Cut connects East Matagorda Bay with the Gulf of Mexico. Prior to 1934, East Matagorda Bay was a direct extension of the larger Matagorda Bay, and the Colorado River emptied directly into the bay at Matagorda. However, in 1929, the Colorado was cleared of a large number of log jams to prevent flooding of interior lowlands. The release of large quantities of sediment caused a delta to build rapidly across the bay, and by 1934 East Matagorda Bay was completely separated from its western namesake (3). Subsequently, direct exchange of bay and gulf waters occurred only through the restricted opening of Brown Cedar Cut.

The natural formation of this inlet probably occurred in 1929, and since then it has remained open over ninety per cent of the time. Available evidence indicates that the inlet width has been highly variable, ranging from a closed condition to as much as six hundred yards. Prior to 1930 the peninsula was wide enough to preclude the existence of a viable channel. Subsequent large-scale erosion of the beach area has markedly reduced the distance between bay and gulf, increasing the likelihood of a permanent inlet. However, its existence and configuration are also dependent upon above average tidal ranges associated with storms and hurricanes, which produce swiftly moving currents with resultant scour of the channel bed. Therefore, descriptions of those storms which may have affected the inlet will be included, and Figure 2 presents the paths followed by the hurricanes discussed.

The following chronological history of Brown Cedar Cut is based on the analysis of photographs and charts compiled from various sources. Chart information is not necessarily presented according to the chart edition date, but is identified with the last year of surveys upon which the chart was based.

1858, Figure 3: The first edition of U. S. Coast and Geodetic Survey charts of East Matagorda Bay indicates Matagorda Peninsula to have been a wide, well-established barrier island, with a low marshy area at its base. The present site of Brown Cedar Cut appeared to be relatively high terrain, not subject to extensive washover during hurricanes.

1875: Mitchell Cut, a long, narrow inlet at the base of the peninsula was formed as a result of a large storm. Large quantities of beach material were washed over the peninsula and the barrier beach topography was greatly altered (37).

1904: Moore reported that during the summer of 1904, closure of Mitchell Cut was accomplished by littoral drift deposition, after a twenty-nine year existence (37). However, it is likely that this cut may have closed and reopened a number of times, since such a pattern is characteristic of small inlets on the Texas coast.

1905, Figure 4: For the most part, the peninsula was relatively unchanged since 1858. An artificial channel at the present site

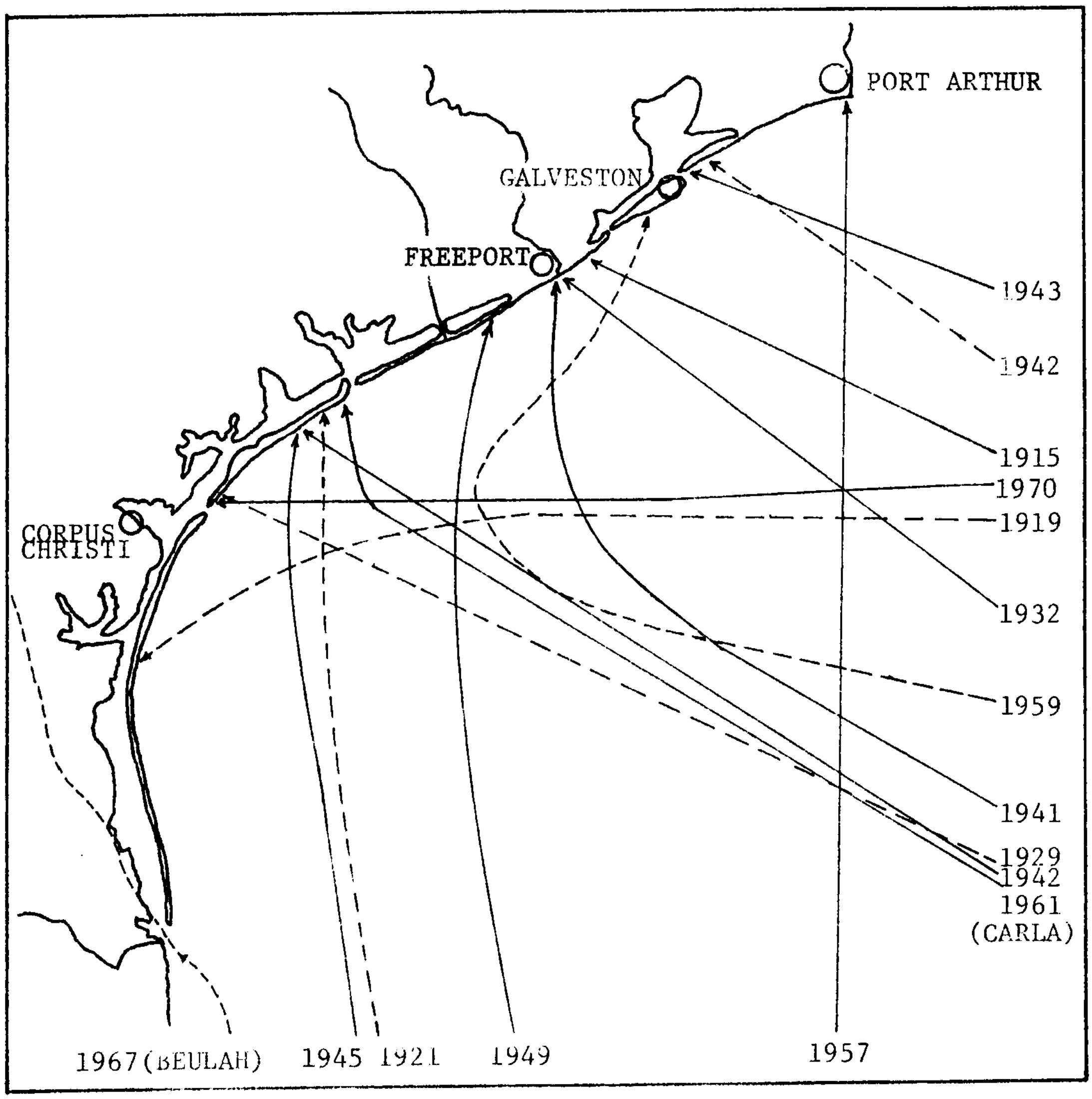



FIGURE 2.--PATHS OF HURRICANES AFFECTING BROWN CEDAR CUT

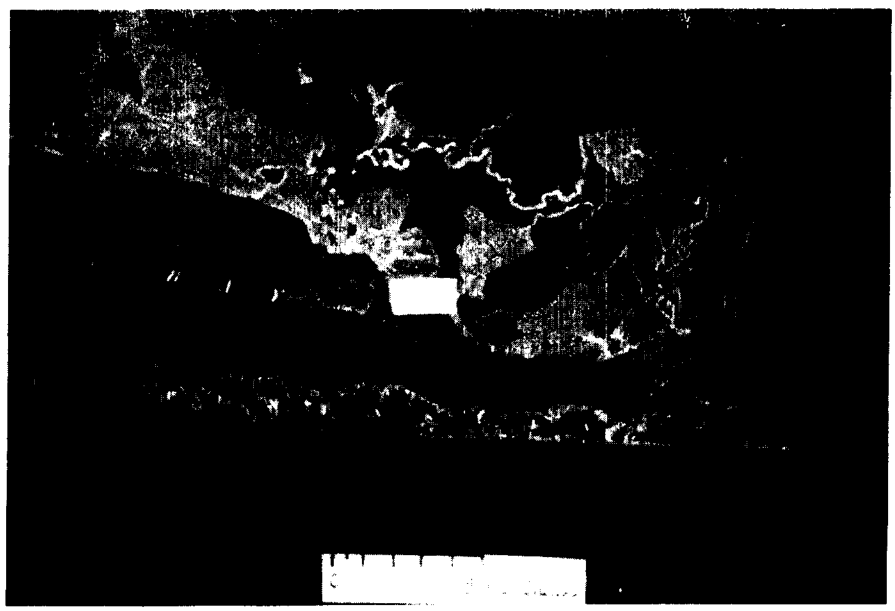


FIGURE 3. EAST END MATAGORDA PENINSULA, 1858.
(AFTER USC&GS CHART 206, 1858)

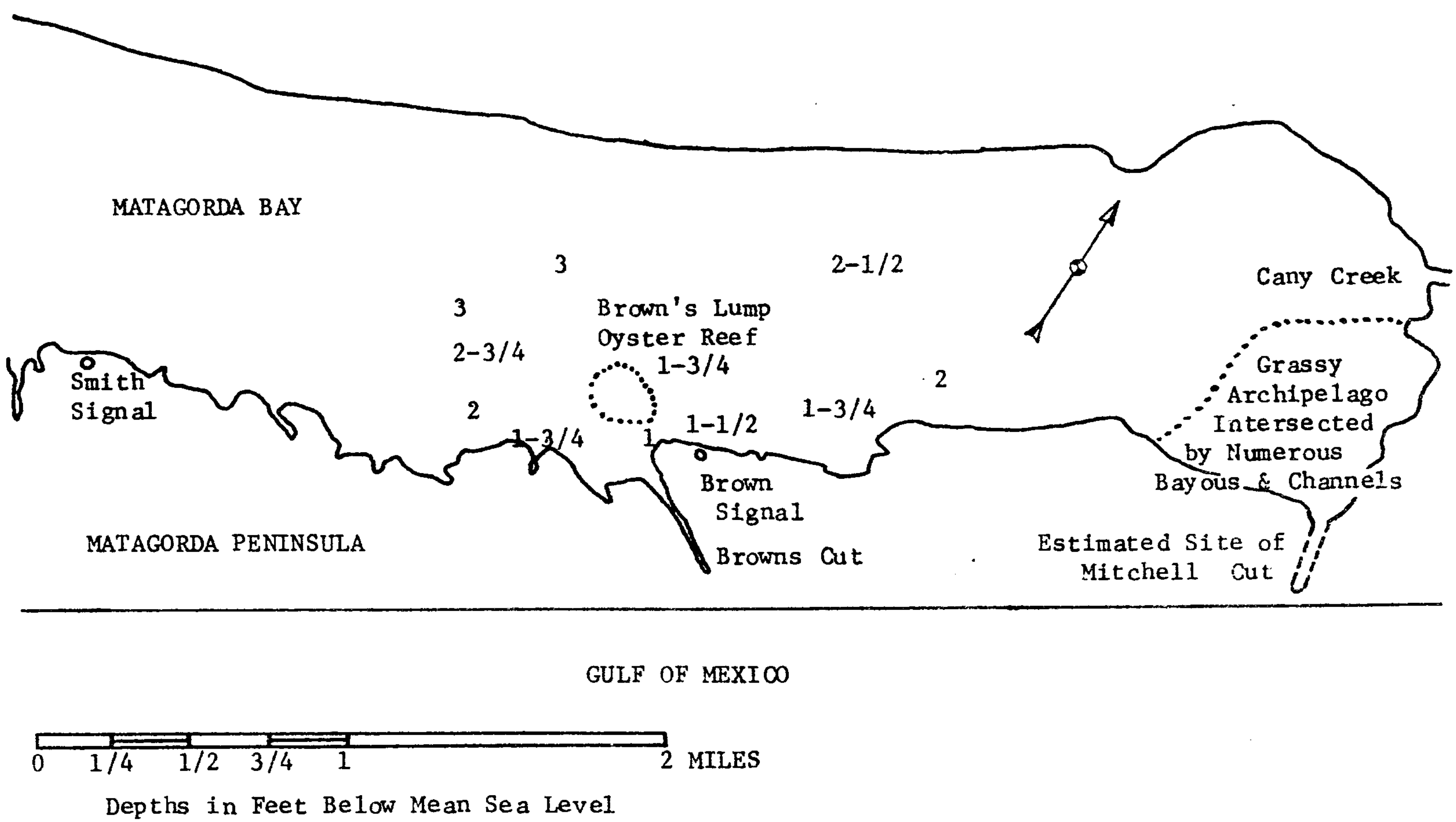



FIGURE 4.—EAST END MATAGORDA BAY, 1905 (AFTER MOORE (37))

of Brown Cedar Cut was dug from the bay almost to the gulf shore. The channel, known as Browns Cut, was excavated by local oyster fishermen to increase the salinity in the bay and thus improve oyster habitats (37). This attempt to open a stable channel apparently failed, for a 1907 coastal chart showed no channel at the site.

1914, Figure 5: Matagorda Peninsula maintained an unbroken profile southwestward from the mainland. The minimum width of the peninsula was approximately eight hundred yards and occurred at the site of Browns Cut. Extensive deposition in the east end of the bay reduced the water depths by about one foot from those of 1858. Shepard (50), in an analysis of sedimentation rates in Texas bays, found that an average depth decrease of one foot occurred in East Matagorda Bay between 1870 and 1934. At the extreme eastern end, however, deposition of as much as two feet was reported. Material deposited between 1858 and 1914 must have been introduced through the Colorado River and the many small creeks which empty into the bay. Cany Creek was probably a prime contributor of east end sediments.

1915: A hurricane of major proportions crossed the coastline about forty miles northeast of Sargent. Storm tides of ten feet above normal were reported at Galveston, and heavy rains occurred over a wide area (46).

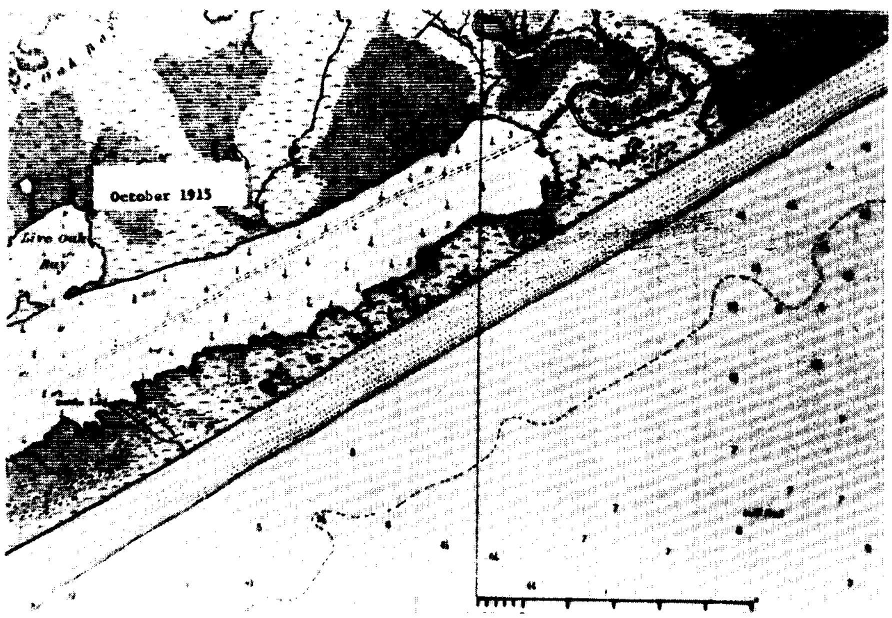



FIGURE 5. EAST END MATAGORDA PENINSULA, 1914.
(AFTER USC&GS CHART 1281, OCTOBER, 1915)

1916, Figure 6: Mitchell Cut reappeared at the extreme eastern end of East Matagorda Bay. This inlet was probably reopened during the breaching of Matagorda Peninsula by the storm tides of the 1915 hurricane. Due to its excessive length, it is likely that Mitchell Cut closed rapidly.

1929: Man's disturbance of two river systems resulted in changes which had major significance to the study area. First, the Colorado River was cleared of log jams and rapid delta building began, as discussed previously. In addition, the Brazos River at Freeport, twenty-five miles northeast, was rechanneled to empty into the Gulf of Mexico at a more southerly location (50). This was done to prevent future flooding of the town, and may have had significant effects upon portions of the coast to the southwest, as shall be discussed later. Of importance is the fact that until 1930, the gulf shoreline south of Freeport had experienced neither deposition nor erosion.

1930, Figure 7: The first documentation of Brown Cedar Cut was presented. USC&GS charts from January 1931 to September 1935 indicate a rather large, straight channel across the peninsula in approximately its present location. Due to the lack of detail, this appears to be more an artist's conception of the inlet than an accurate map, unless a channel was artificially created, as in the case of Browns Cut. Although this is possible, the extensive size of the channel suggests a natural origin.

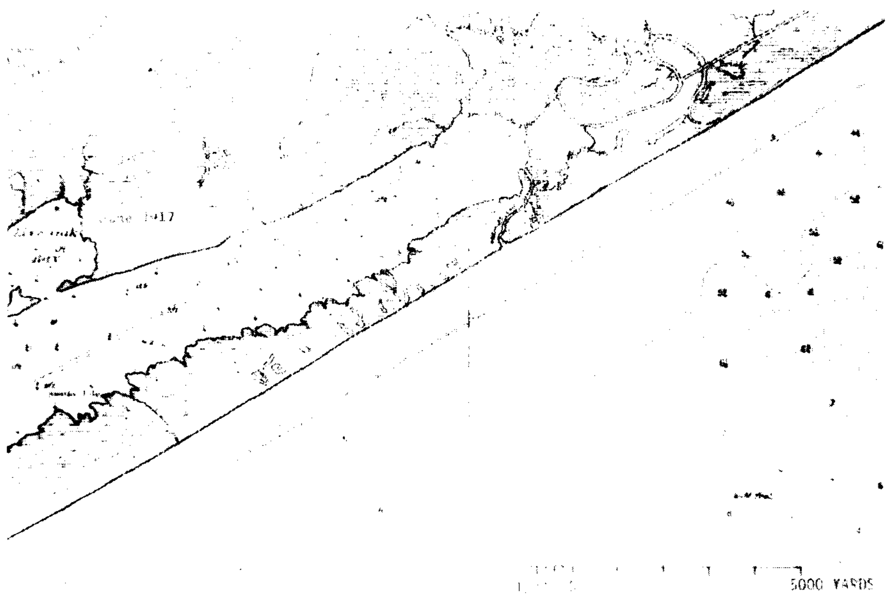



FIGURE 6. EAST END MATAGORDA PENINSULA, 1916.
(AFTER USC&GS CHART 1281, JUNE, 1917)

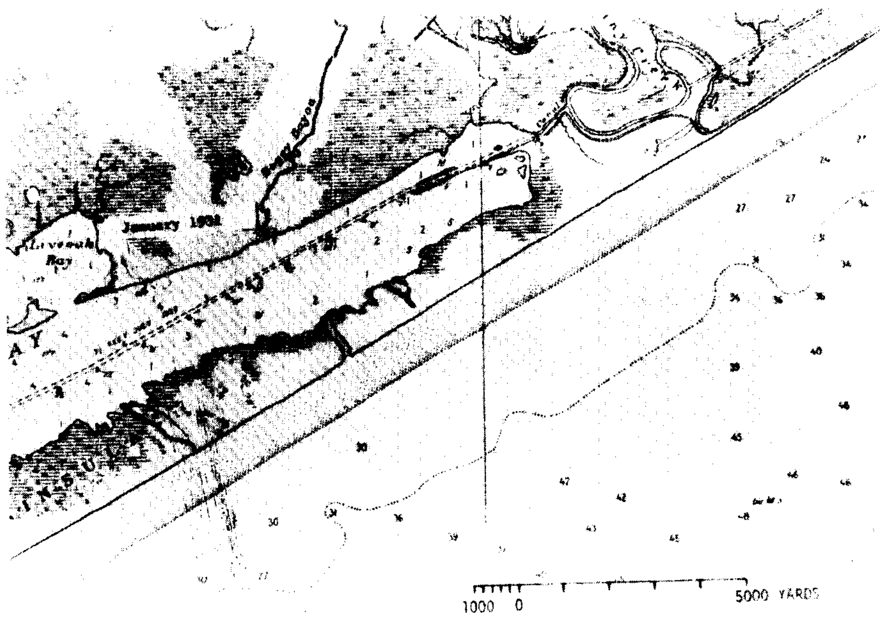



FIGURE 7. EAST END MATAGORDA PENINSULA, 1930.
(AFTER USC&GS CHART 1283, JANUARY, 1931)

Figure 7 also presents evidence of dredging of the Intracoastal Waterway through the bay. Such activity, in combination with the continuing siltation from freshwater runoff, could have caused the filling of the marshy lowlands near Mitchell Cut. Such depositional patterns are likely to have resulted in the requirement that a more efficient location for the exchange of bay and gulf water be established. As indicated in previous figures, the narrowest portion of the peninsula, and therefore a likely site for this new channel, was the site occupied by Brown Cedar Cut in 1930.

Assuming a natural origin, it appears that formation of Brown Cedar Cut occurred during a period of high water between 1916 and 1930. Returning to Price (46), it is found that hurricanes which could have affected that portion of the coast occurred in 1919, 1921, and 1929. It is the latter of these which is of interest, for it crossed the coast about forty-five miles south of the site of Brown Cedar Cut. Storm tides at the site are estimated to have been about five feet. The hurricane of 1919 was of much greater magnitude, inundating the entire peninsula with nine foot storm tides and exposing the beaches and dunes to the scouring action of high waves and currents (46). However, evidence discussed below indicates that formation in 1929 was more likely.

1932: A small hurricane crossed the coast at Freeport (46). Winds at Brown Cedar Cut would probably have been from the northeast, forcing water out of the bay through the cut.

1934: Building of the Colorado River delta was completed, and the river emptied directly into the Gulf of Mexico (3).

1935, Figure 8: Widespread shoaling of the eastern bay since 1930 is indicated. Sedimentation occurred both at the extreme eastern end, which served to further stabilize the low-lying areas at the base of the peninsula, and in the bay adjacent to Brown Cedar Cut. That such filling occurred as a result of the Colorado delta building is doubtful, for Shepard (50) reports that sediments from this source were transported in a predominately westward direction by prevailing winds. Dredging and surface runoff are also considered to be unlikely sources of the large volumes of sediment deposited. Therefore, it appears that this deposition occurred almost entirely from the opening of Brown Cedar Cut. This important fact helps to establish the date of origin of the inlet. If it were formed in 1919 or 1921, extensive shoaling of the bay adjacent to the channel should be apparent in 1930 (Figure 7). However, such evidence is lacking, and the conclusion is reached that Brown Cedar Cut was first scoured by the hurricane of 1929.

Comparison of the 1930 and 1935 shorelines presented in Figure 9, indicates that significant erosion of the gulf shoreline occurred in the intervening years, with about three hundred fifty yards of beach lost on either side of the inlet. Although a hurricane did strike the coast in 1932, examination of additional charts revealed that continued erosion occurred only from the Brazos River to about

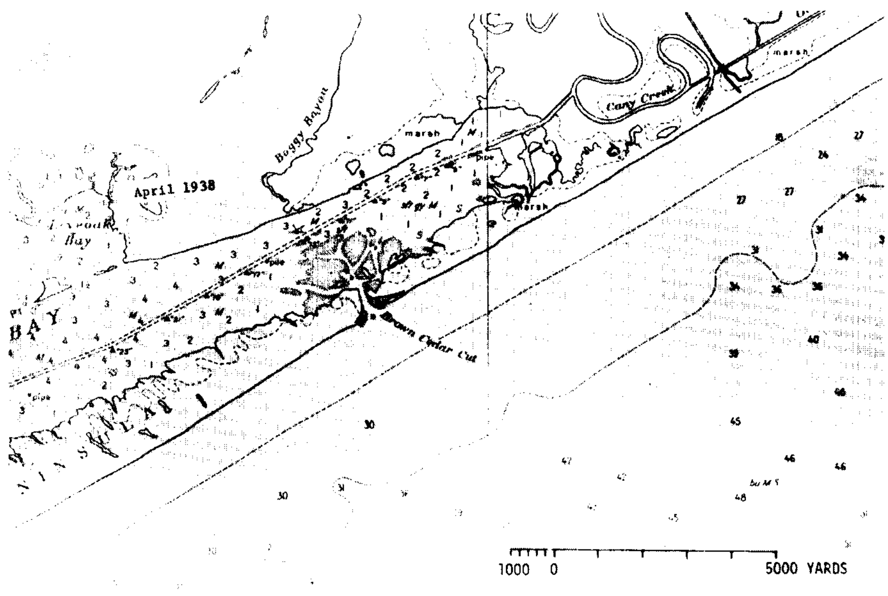



FIGURE 8. BROWN CEDAR CUT, 1935.
(AFTER USC&GS CHART 1283, APRIL, 1938)

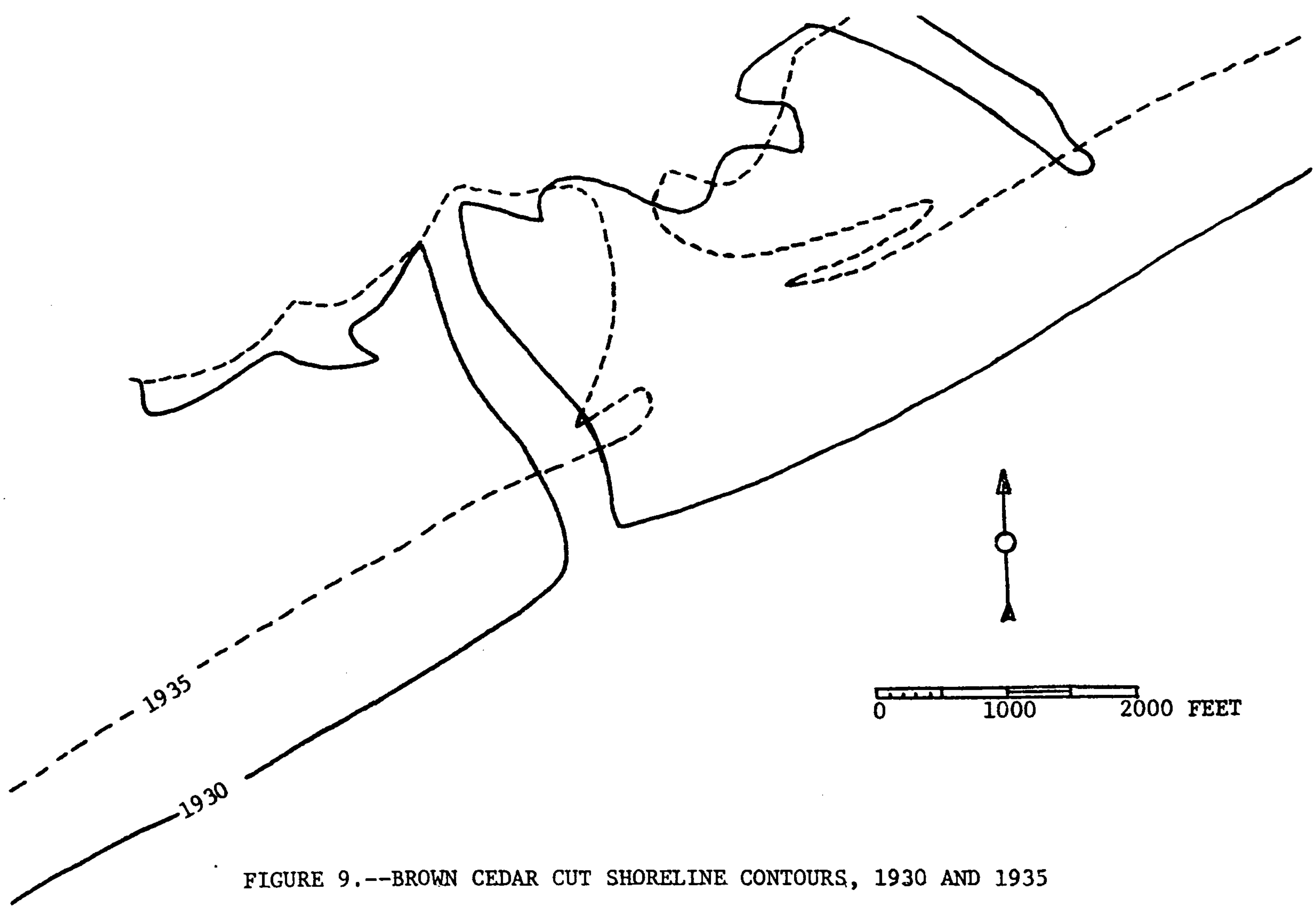



FIGURE 9.--BROWN CEDAR CUT SHORELINE CONTOURS, 1930 AND 1935

ten miles west of Brown Cedar Cut. Therefore, some other source of the observed erosion is suggested. The only known major modification to upcoast regions was the rechanneling of the Brazos River, which could have disturbed the equilibrium conditions in two ways. First, the introduction of a deep, wide channel must have effectively interrupted the predominate transport of littoral drift to the west. Natural by-passing probably requires a considerable period of time to become established, and the deficit in suspended material would have caused erosion of downcoast beaches. Secondly, charts of the area indicate that a delta grew rapidly into the gulf. This process consumed river sediment which would otherwise have been introduced into the longshore transport patterns, contributing to the stability of beaches to the west.

1938, Figure 10: No changes in the bay islands and shoals are shown, but the channel widened to about two hundred yards. Although the beach areas immediately adjacent to the inlet did not experience erosion, over seventy yards were lost from more distant sections on either side, as illustrated in Figure 11.

1941: A hurricane of major proportions crossed the coast near Freeport, producing storm tides of approximately ten feet at Brown Cedar Cut (14).

1942: Two large hurricanes inundated the area with tides of ten feet or more (21).

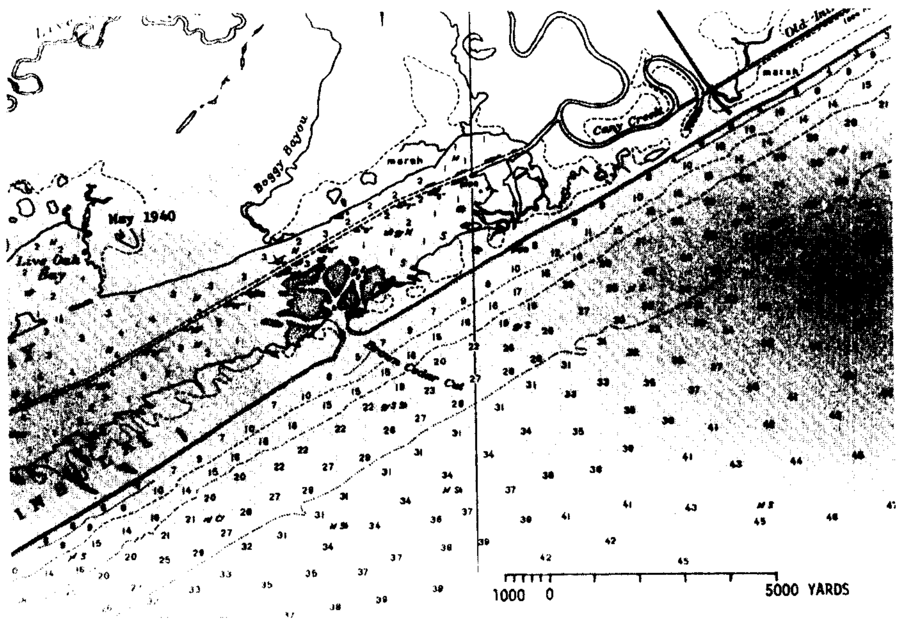



FIGURE 10. BROWN CEDAR CUT, 1938.
(AFTER USC&GS CHART 1283, MAY, 1940)

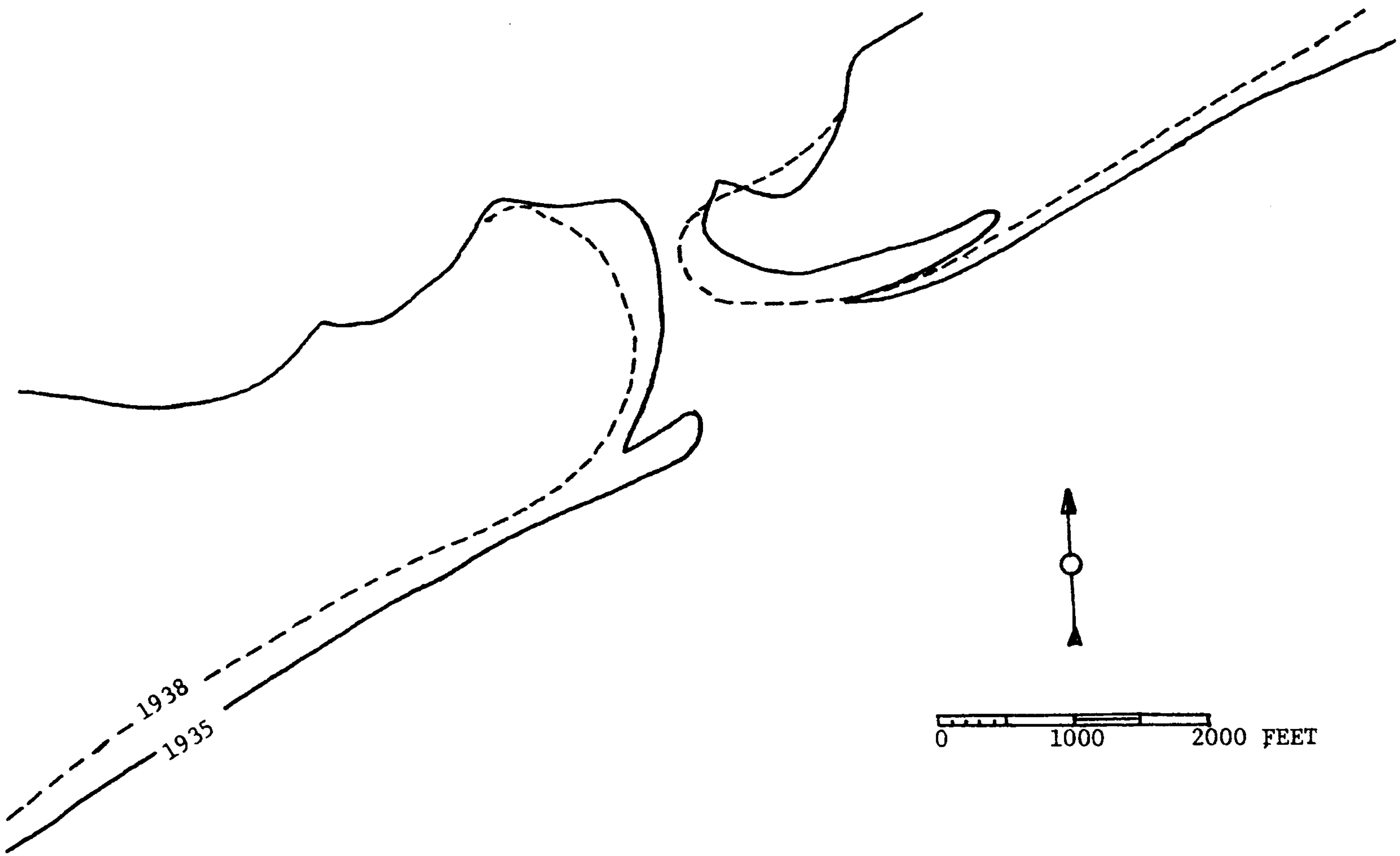



FIGURE 11.--BROWN CEDAR CUT SHORELINE CONTOURS--1935 AND 1938

1943: Sometime between 1938 and 1943 the Intracoastal Waterway was rerouted to a dredged channel on the mainland shore, and dredging in the bay ceased. Exchange of water between the deep dredged channel and East Matagorda Bay took place only at the intersection of the old and new channel near Caney Creek.

In July, 1943, a hurricane of unknown proportions crossed the coast at Galveston (14).

In October, 1943, the first photographic coverage of the area, Figure 12, indicates a wide, shallow opening at Brown Cedar Cut resulting from the passage of the three hurricanes. The channel exhibited a predominately north-south orientation which was not previously indicated. Such orientation is typical of other inlets on the Texas coast, although they are usually located at the southwestern end of their adjoining bays. Price, in an analysis of central Texas coastal inlets (44), attributes these characteristics of stable inlets to four factors: 1) the position of bays north of the barrier island, 2) strong north winds which funnel water through the inlets, 3) the direction of longshore drift, and 4) the orientation of the barrier island coastline. Although Brown Cedar Cut is located at the northern end of the bay, orientation of the inlet in 1943 was still probably due to northerly winds associated with the 1943 Galveston hurricane. Further comparison indicates that the shoal areas in the bay grew significantly since 1938 and acquired a mantle of protective vegetation. These areas experienced little

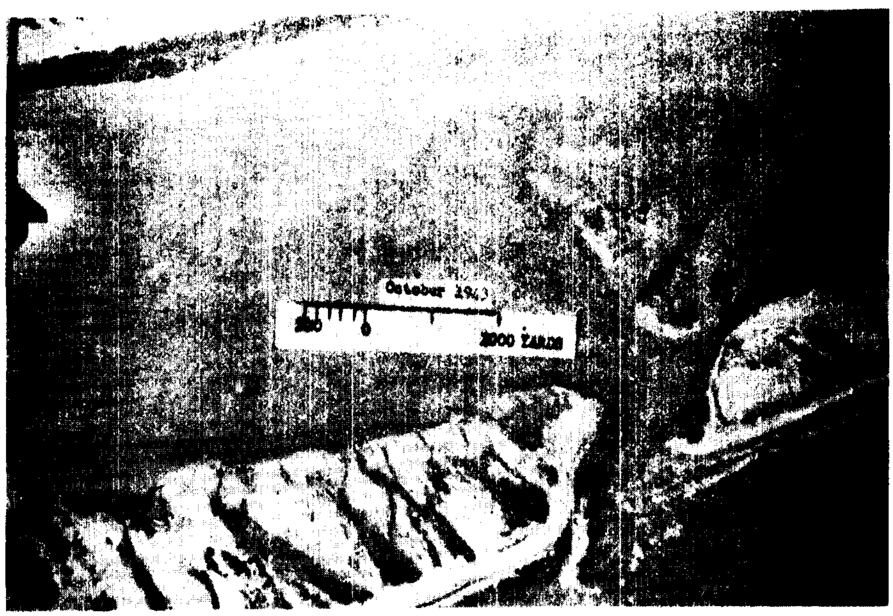



FIGURE 12. BROWN CEDAR CUT, OCTOBER, 1943.
(PHOTO COURTESY [illegible])

future growth or degradation, and serve as excellent reference points for analysis of channel migrations.

It should also be noted that the shorelines on either side of the inlet no longer coincide with a single straight line. If a tangent to the southwest shoreline is extended toward the opposite shore, as indicated by the dotted line in Figure 12, this offset condition is seen to amount to about three hundred feet. Price (44) felt that the offset probably resulted from the existence of littoral drift arriving from the northeast, and defines a typical sequence of events occurring at a stable inlet: Sand moves from the northeast to the inlet, and rather than being deposited on the northeast side, is introduced into the normal ebb and flow of tidal currents. Some of this sand drifts across the inlet and accumulates on the southwest bank, and this side becomes excessively large in the stable position. In a more recent paper, Hayes (23) reports that the offset condition can result from wave refraction patterns associated with offshore shoal areas. In the case of Brown Cedar Cut, waves arriving from the east and southeast are refracted about the gulf bars. This action produces a local reversal of predominate longshore currents on the west side, and deposition occurs adjacent to the inlet mouth.

1945: A hurricane of major proportions affected most of the Texas coast. Tides at the site were about ten feet and hurricane force winds lashed the area (46).

1949: A hurricane passed directly over the site, and tides are estimated to have been about eleven feet. Two small openings were cut in the peninsula between Brown Cedar Cut and the Colorado River, but closed rapidly (42).

1953, Figure 13: Photographic coverage indicates continued building of shoal areas in the bay and the growth of a large spit toward the southwest. The offset condition exhibited in 1943 was accentuated, and amounted to a difference of four hundred feet between shoreline tangents. Comparison of the two years' profiles is presented in Figure 14, and, contrary to the theories discussed above, indicates that substantial erosion of the northeast shore is responsible for the increased offset. Thus, it would appear that the amount of littoral drift transported to the inlet from the northeast was not sufficient to meet the equilibrium demands of beaches in that direction. On the southwest side, however, the sand supply was apparently sufficient to allow reasonably stable conditions. If the wave climate was identical on both sides of the inlet, then the inlet itself must have supplied the necessary sediment. However, since the predominant wave direction is from the southeast, it is more likely that the previously discussed refraction of wave fronts reduced the effective wave energy reaching the southwest side and permitted equilibrium beach conditions. Whatever processes produced this offset, their activity during the ten years prior to 1943 was significantly greater than during the ten years between 1943 and 1953.

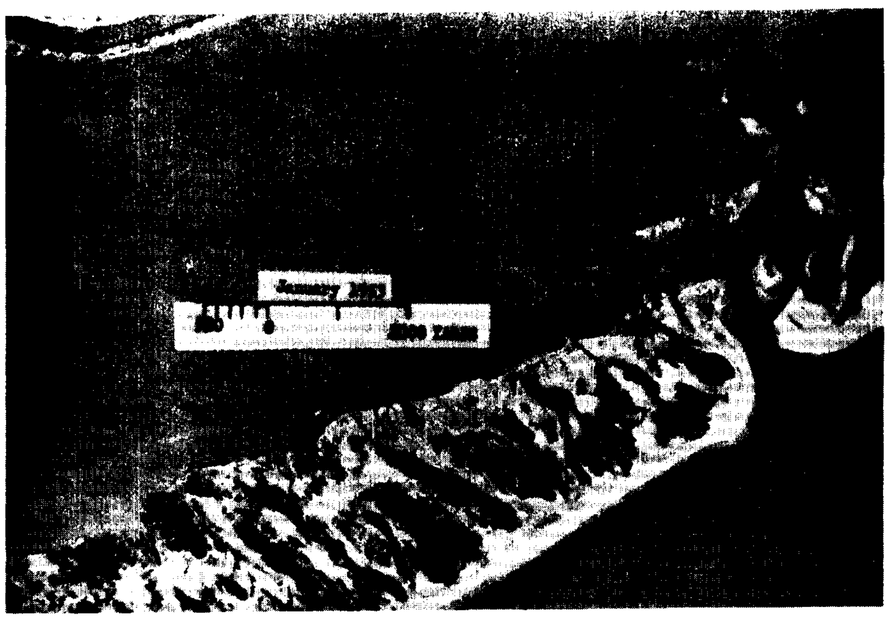


FIGURE 13. BROWN CEDAR CUT, JANUARY, 1953.
(PHOTO COURTESY USDA)

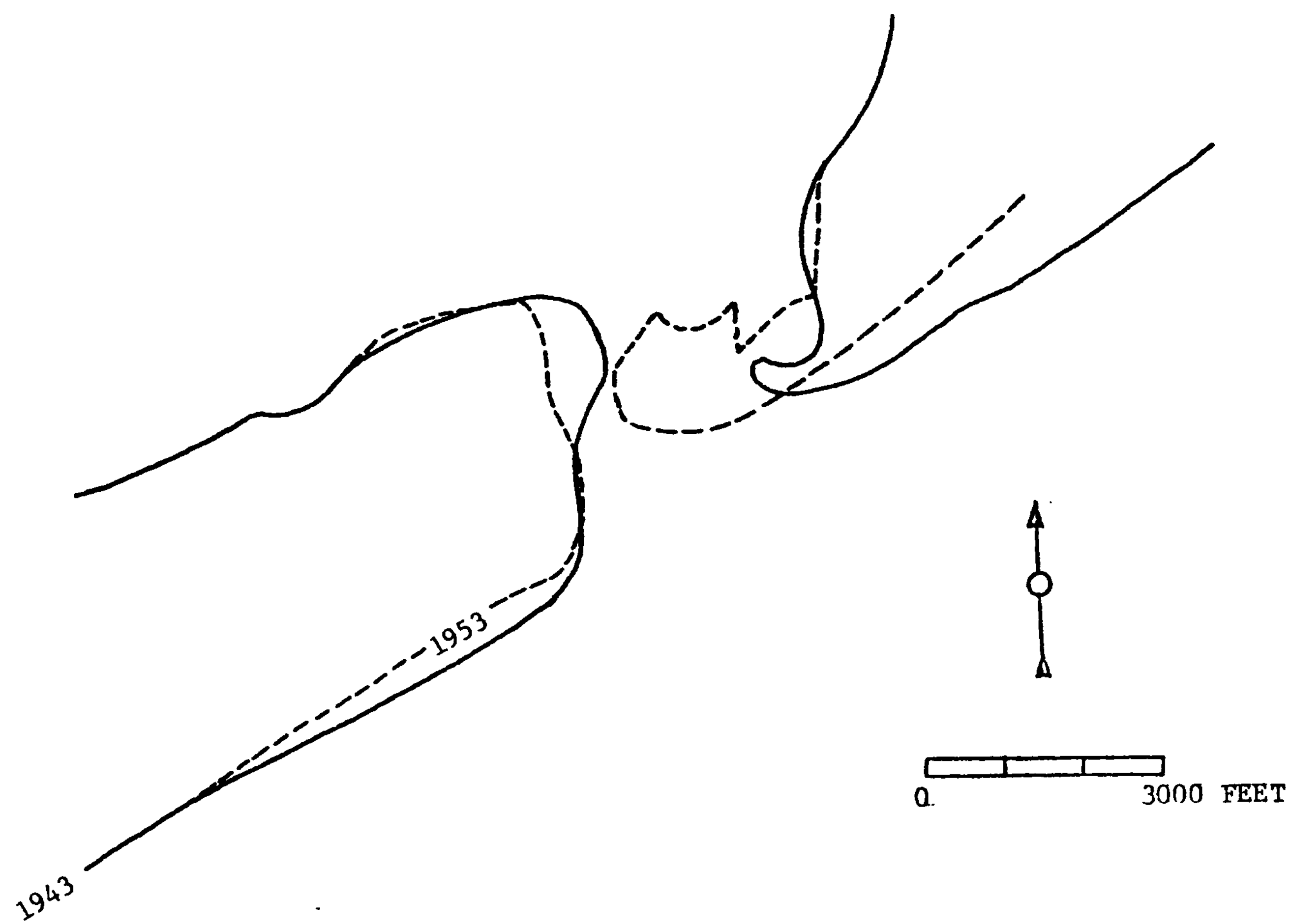



FIGURE 14.--BROWN CEDAR CUT SHORELINE CONTOURS--1943 AND 1953

1954, Figure 15: A detailed survey of Brown Cedar Cut was performed as part of a study of fish passes on the Texas coast (32). The gorge closely skirted the southwest bank and the major connection with the bay extends westward from it. Although this survey was performed in 1954, it bears great resemblance to the photograph taken in 1953, and has been used as a source for establishing the proper photographic scale.

1957: Hurricane Audrey crossed the Louisiana coast near Port Arthur, Texas, causing storm tides of about four feet at Brown Cedar Cut. The maximum high water was followed by a rapid lowering of sea level due to north winds (21), and considerable scour of the channel may have occurred.

1958, Figure 16: The spit on the northeast side continued to build toward the southwest, and the mouth of the inlet migrated about one hundred seventy yards from its position in 1954. Comparison of the 1958 contours with those of 1953 is shown in Figure 17. Of prime importance is the fact that while the offset condition existed in 1953, erosion of only the southwest bank transpired until, by 1958, both shorelines once again coincided with a single straight line. Whether such realignment occurred gradually over the intervening five years or was due to the passage of Hurricane Audrey is unknown, but it does indicate that the offset condition, so characteristic of Texas inlets, may be subject to eradication under certain environmental conditions. Also noted is the shift of the

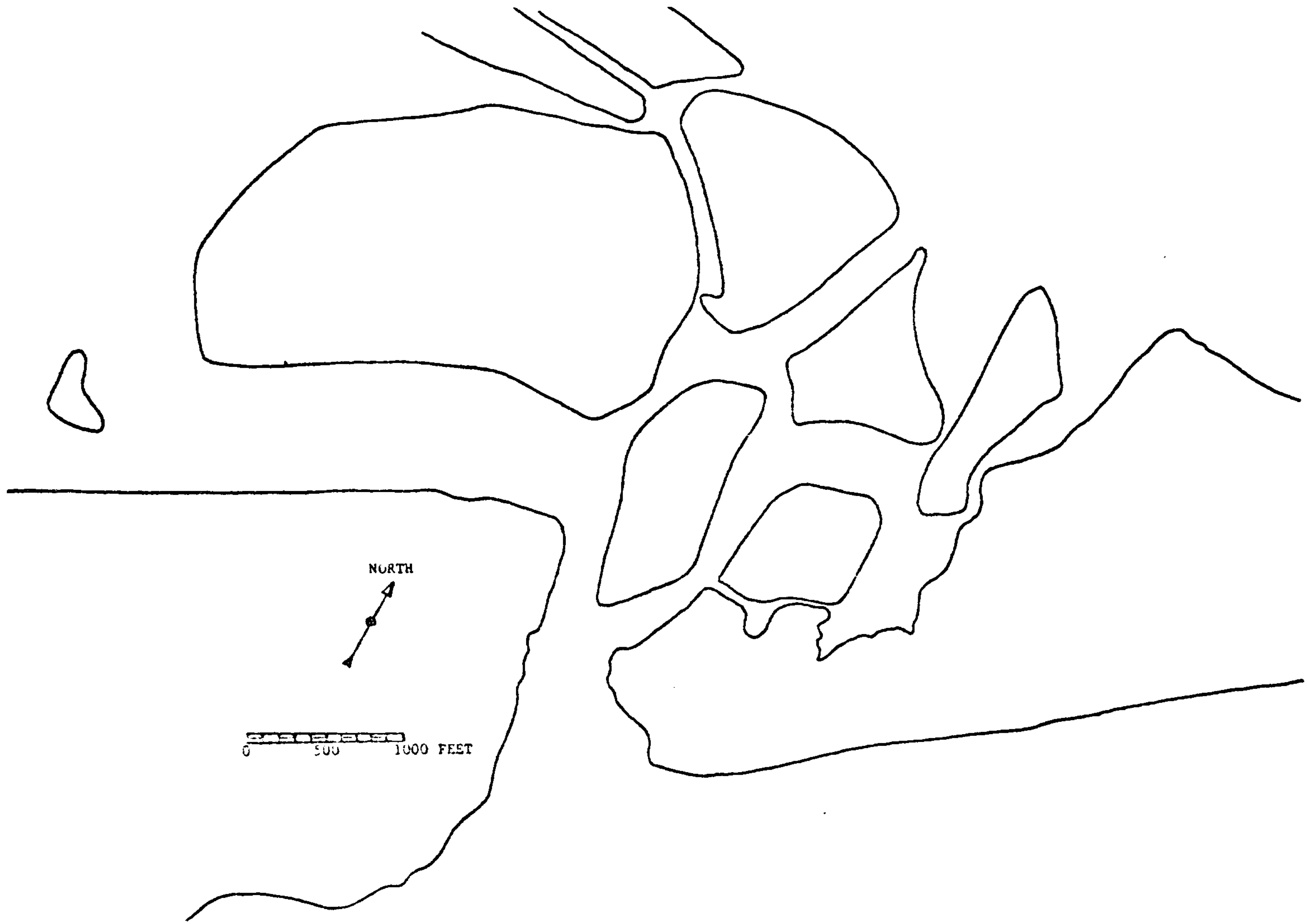



FIGURE 15.--BROWN CEDAR CUT MEAN SEA LEVEL CONTOURS, FEBRUARY, 1954. (AFTER (32))

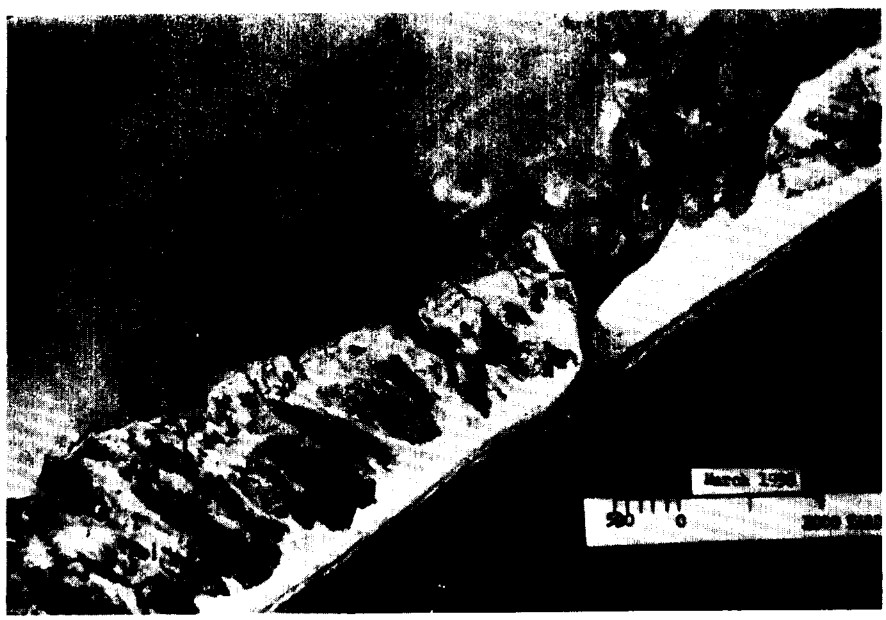


FIGURE 16. BROWN CEDAR CUT, MARCH, 1958.
(PHOTO COURTESY USDA)

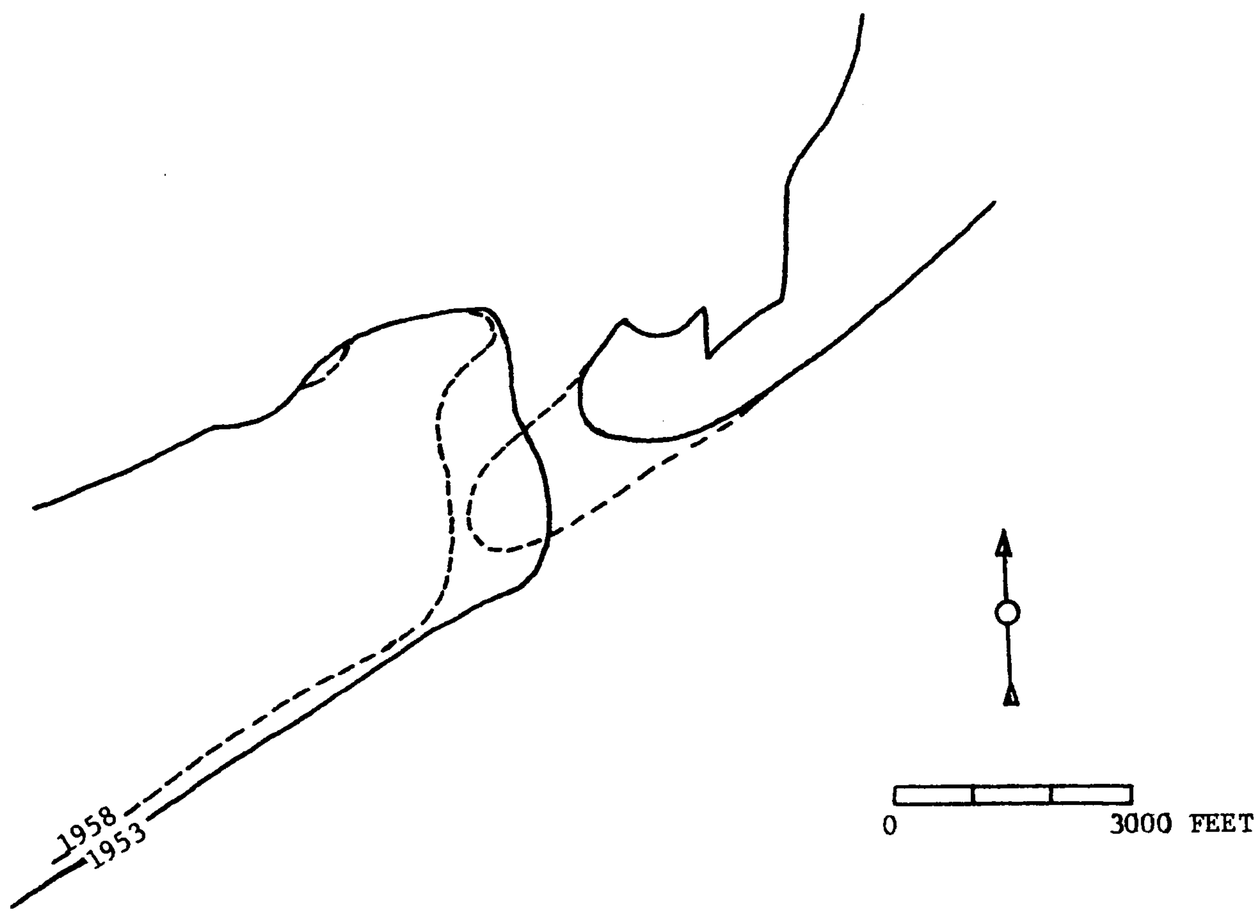



FIGURE 17.--BROWN CEDAR CUT SHORELINE CONTOURS--1953 AND 1958

main bay channel to a more easterly location and considerable siltation of the 1953 channel.

1959: Hurricane Debra crossed the coast near Galveston in July, but information concerning its effects on Brown Cedar Cut was not available (14).

1960, Figure 18: Continued elongation of the inlet provides evidence that Debra's effects on the area were negligible. The controlling width of the channel was only about one hundred feet, and closure appeared imminent.

1961: Perhaps the most devastating of all hurricanes to strike the Texas coast came ashore near Port O'Conner, about forty-five miles southwest of Brown Cedar Cut. Storm tides at Matagorda were measured at 11.6 feet and once again the entire Matagorda Peninsula was inundated (52). According to residents of the area, Carla opened a very wide shallow breach at Brown Cedar Cut. This would seem to indicate that the dominant processes acting to modify the inlet were wave action combined with high water. Outflow from the bay, which occurred during the gradual ebb of the storm tides, was apparently well distributed along the peninsula, and high velocities were probably not produced, since deep scour of the inlet was absent.

1963: Hurricane Cindy crossed the Bolivar Peninsula at High Island in September, but this storm's effect upon central Texas beaches was quite minor (22). A tide of one foot above normal is

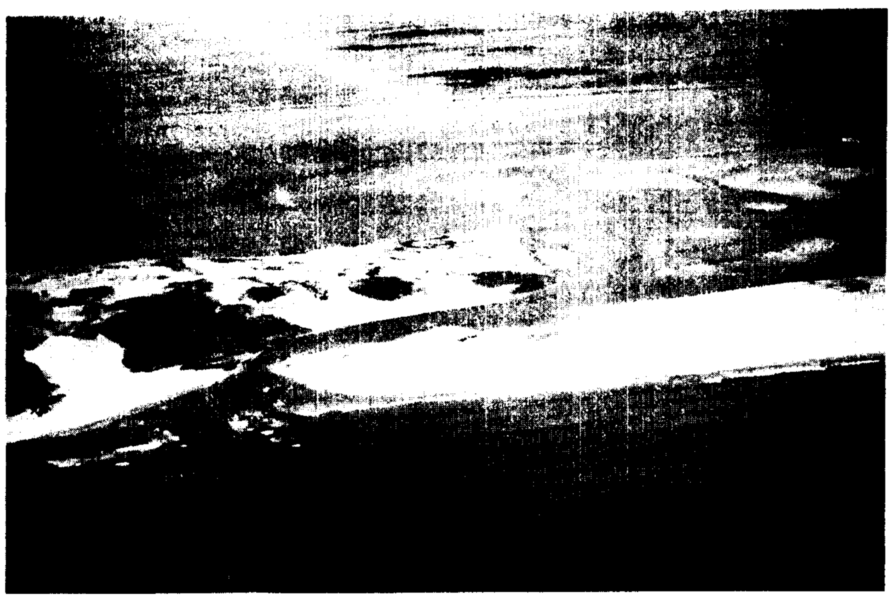


FIGURE 18. BROWN CEDAR CUT, JUNE, 1960.
(PHOTO COURTESY TEXAS PARKS AND WILDLIFE)

estimated for the site, and acting in concert with moderately high waves, the inlet may have been widened.

1964, Figure 19: Widening of the inlet by Carla and perhaps Cindy is clearly indicated. The exact date that surveys for this chart were taken is unknown, but it was prior to February, 1964. That such widening eventually lead to the closure of the inlet is substantiated by the fact that in late 1964, complete filling of the channel was accomplished (34). Price reports a similar closure of Cedar Bayou on St. Joseph's Island after passage of the 1929 hurricane (43).

1965, Figure 20: In 1965, attempts were made by local citizens to reopen the inlet. Using a bulldozer and a drag-line dredge, a long narrow channel was excavated to connect the bay and gulf. This channel remained open about one week, and then filled with sand. Remnants of the channel can be seen in the left center of Figure 20.

1967: Under the influence of Hurricane Beulah, Brown Cedar Cut reopened. Storm tides at the site were about five feet, and wave activity was high (54). The storm surge profile for Freeport, shown in Figure 21, indicates that outflow from the bay may have been important to the reopening of the inlet, since prevailing ebb conditions could have produced significant velocities through the channel.

1969, Figure 22: Although no major storms were reported between November, 1967, and June, 1969, it appears that the inlet

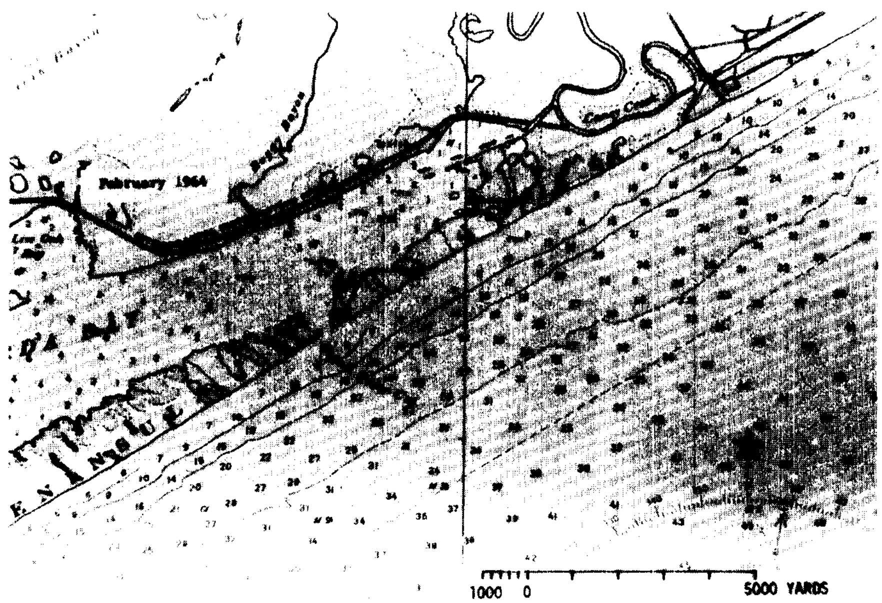



FIGURE 19. BROWN CEDAR CUT, 1964.
(AFTER USC&GS CHART 1283, FEBRUARY, 1964)


FIGURE 20. SITE OF BROWN CEDAR CUT, OCTOBER, 1965.
(PHOTO COURTESY USDA)


FIGURE 21.--HURRICANE BEULAH SURGE RECORD, FREEPORT, TEXAS (AFTER (54))

FIGURE 22. BROWN CEDAR CUT, JUNE, 1969.
(PHOTO COURTESY TEXAS PARKS & WILDLIFE)

maintained satisfactory geographic stability. It is unfortunate that a 1967 post-Beulah photograph was not available, for the inlet must have been of significant proportions and quite deep. Note that almost no spit building has occurred on the northeast side and than only minor shoal areas flank the main channel outside the mouth.

1970: Hurricane Celia, which struck the Corpus Christi area in August, produced a storm surge of about two feet at Brown Cedar Cut, and wave activity was great. A wide channel was observed shortly after Celia's passage, and it did not significantly alter shape prior to the first survey conducted by the author in October, 1970. The inlet configuration in November is presented in Figure 23, but modifications which occurred after October will be discussed in a later section.

FIGURE 23. BROWN CEDAR CUT, NOVEMBER, 1970.
(AUTHOR'S PHOTO)

# HYDRAULIC PROPERTIES

The characteristics and stability of a tidal inlet are governed primarily by the exchange of water through its channels between the ocean and enclosed bay. This exchange results from differences in water level between the channel ends as the ocean tide pursues its rhythmic fluctuations, but is also influenced by locally generated wind tides. The quantity of water exchanged and the velocities developed through the inlet are dependent upon the magnitude of the astronomical and meteorological tidal differentials. In order to determine the hydraulic properties at Brown Cedar Cut, it was necessary to obtain a continuous record of either the velocity or the tidal differential. Since instrumentation of the inlet for velocity information was prohibitively expensive and subject to interference by natural and human forces, a plan for installation of two recording tide gages was implemented. From the information gathered by these gages, flow characteristics were determined using widely accepted hydraulic relationships.

## Tidal Data

Collection of tidal data was performed using Leupold & Stevens Water Level Recorders (Type F, Model 68) which were installed at the positions indicated in Figure 24. Since permanent structures in the gulf were not available, gage Number 1 was mounted on a small wooden dock about mid-way through the inlet. Comparison

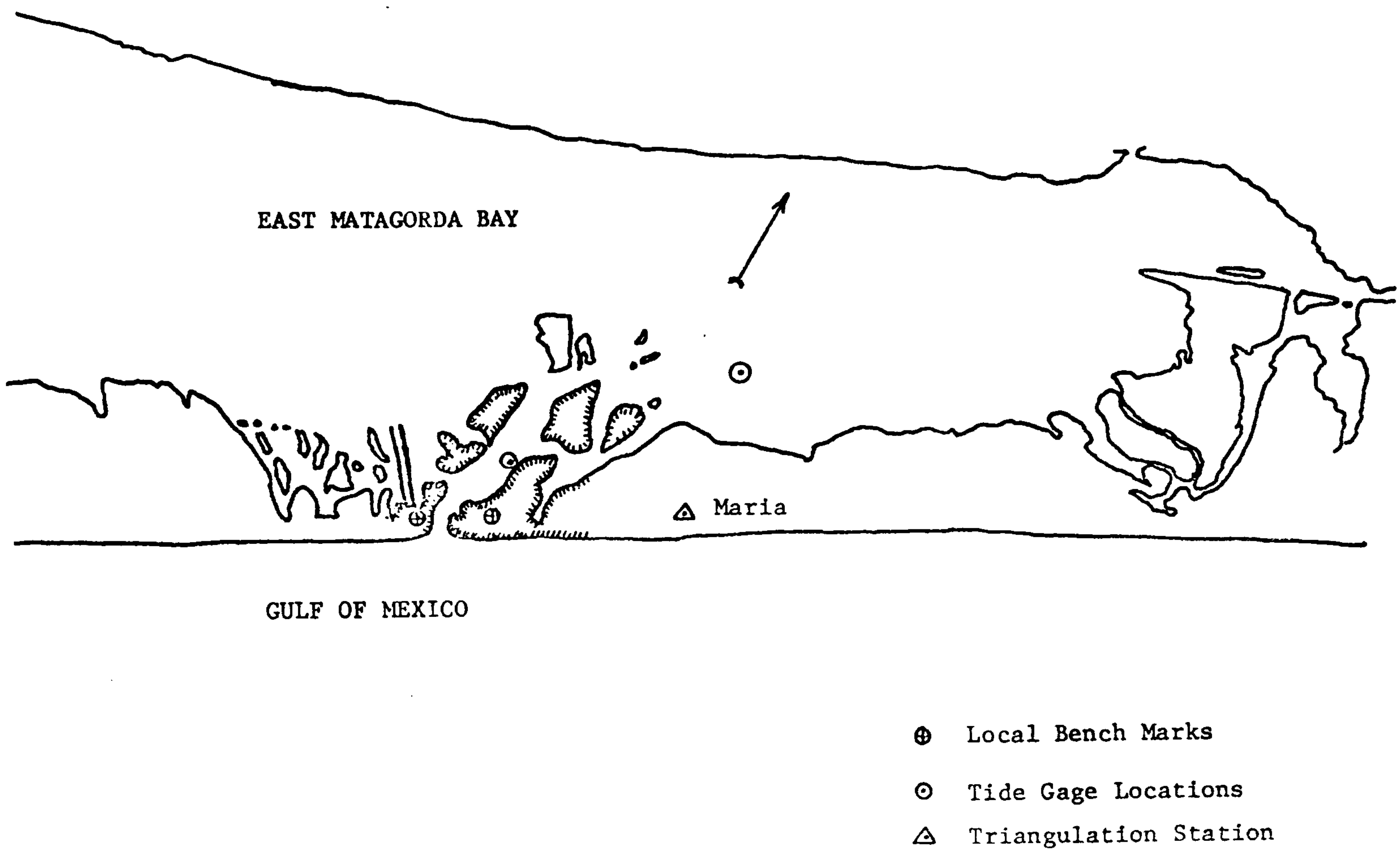



FIGURE 24.--POSITIONS OF SEMI-PERMANENT MARKERS, BROWN CEDAR CUT

of tidal records from this gage with those provided by the U. S. Army Corps of Engineers for Freeport, Texas, indicated that for the purpose of this study, no significant differences in magnitude or phase occur. Gage Number 2 was mounted on an abandoned piling, and provided accurate measurements of local bay fluctuations. The recorders were operated from February 1 to April 9, 1971, and although they experienced equipment or operator error at times, sufficient data were collected to allow meaningful calculation of tidal differentials over most of the recording period. The large volume of tidal data precludes publication of individual records, but significant aspects of the tidal history will be discussed.

Analysis of the records was performed to determine the mean water level (MWL) over the reporting period. This value was determined by averaging a series of inlet water level elevations at two hour intervals, which were referenced to an arbitrary datum. The averaged value was established as the mean water level for both gulf and bay records. The relative elevation of the bay gage was determined by running a level line from the inlet tide staff to that of the bay location. In addition to establishing the MWL value, other tidal data required for future calculations were obtained, and are presented in Table 1.

The time history of tidal differential is presented in Figures 25 and 26. Negative tidal differentials predominated over the recording period, meaning that the bay level was usually higher than

| Tide Gage | Mean Low Water | Mean High Water | Mean Range | Maximum Low Water | Maximum High Water | Maximum Range |
|---|---|---|---|---|---|---|
| #1 (Inlet) | -.44 | +.37 | .81 | -2.40 | +1.40 | 3.80 |
| #2 (Bay) | -.10 | +.14 | .24 | -.92 | +1.20 | 2.12 |

TABLE 1.--TIDAL CHARACTERISTICS AT BROWN CEDAR CUT, FEET FROM MWL DATUM, FEBRUARY 1 TO APRIL 9, 1971.

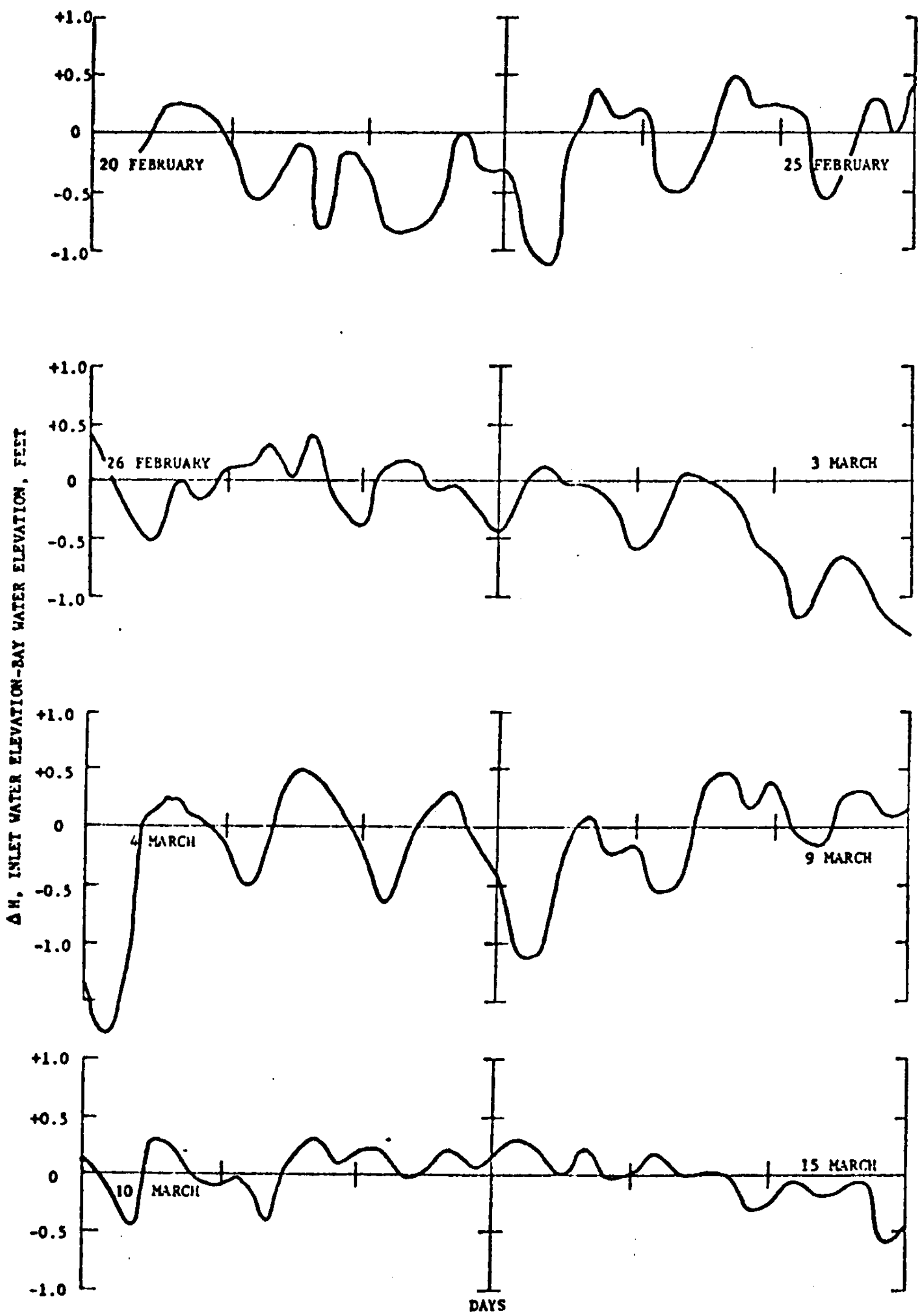



FIGURE 25.--TIDAL DIFFERENTIAL, 20 FEBRUARY TO 15 MARCH, 1971

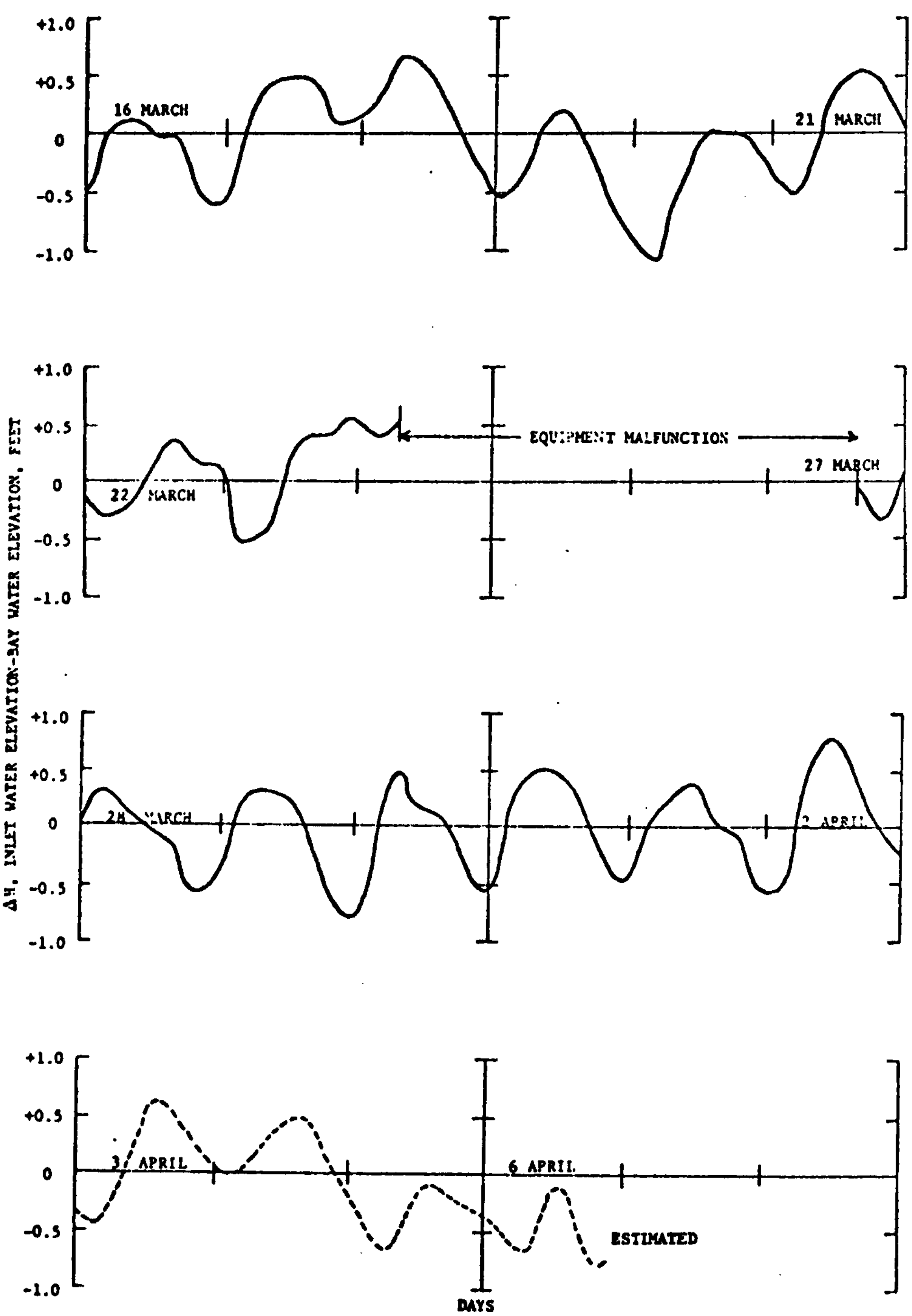
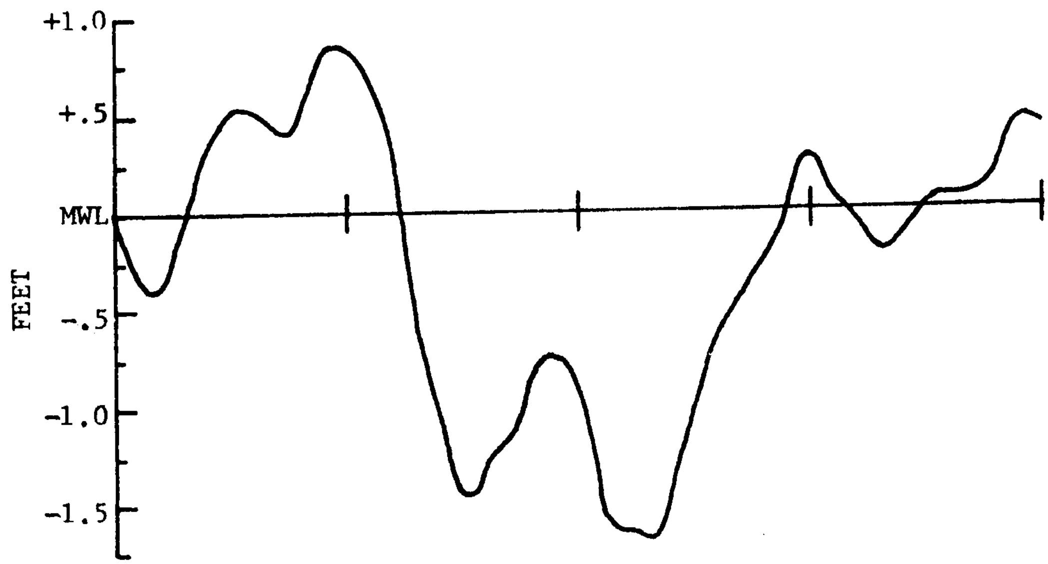



FIGURE 26.--TIDAL DIFFERENTIAL, 16 MARCH TO 6 APRIL, 1971

that of the gulf. The greatest differentials occurred when winds from the north forced water to pile-up on the bay side of the barrier beach and flow rapidly through the inlet. To determine the magnitude of such locally generated water level fluctuations, detailed analysis of the tidal records during a representative period was performed.

The period between March 2 and March 5, 1971, was selected because the effects of a typical winter norther were superimposed on spring tide conditions. The non-astronomical tide was obtained by subtracting the predicted tide at Brown Cedar Cut (corrected from Galveston daily predictions) from the observed inlet tide gage record. The resulting values represent the non-astronomical sea level. Miller (36) found that the observed response of the water surface to changes in atmospheric pressure, i.e. the barometric effect, could be expressed by the theoretical equilibrium value, one inch of mercury per 13.6 inches of water. Using this relationship, the barometric effect was eliminated from the time history of nonastronomical sea level, and the resulting curve is presented in Figure 27. Climatological data supplied by the National Oceanic and Atmospheric Administration provided atmospheric pressure and wind conditions for the reporting period, and wind characteristics are also presented in Figure 27.

Figure 27 indicates that during the reporting period, the wind produced a maximum water surface lowering of 1.7 feet below mean




NON-ASTRONOMICAL SEA LEVEL, CORRECTED FOR BAROMETRIC EFFECT

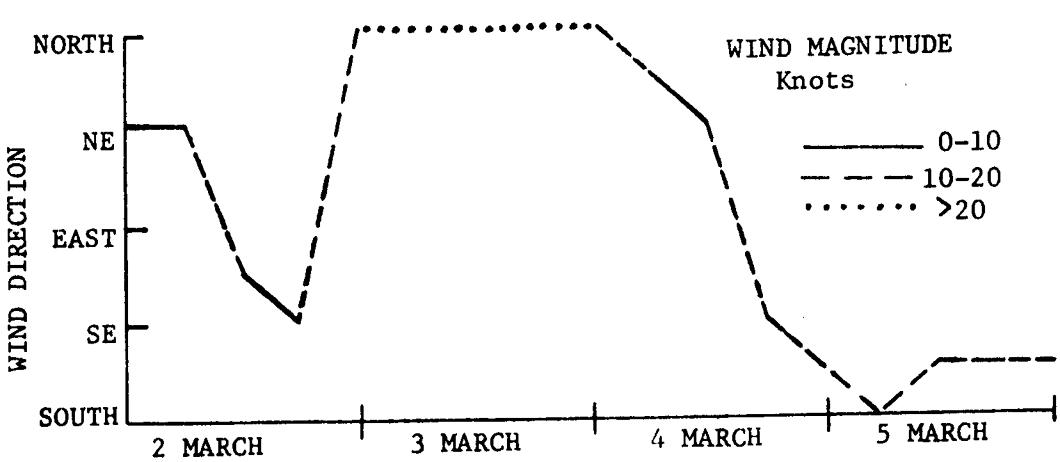



FIGURE 27.--NON-ASTRONOMICAL SEA LEVEL AND CORRESPONDING WIND REGIMES, INLET TIDE STATION

water level. The response time between a shift in wind direction and the corresponding change in water surface elevation is apparently quite short, and the time lag between wind shift and maximum setup was about the same as the twelve hours reported by Miller. Although wind effects are well illustrated, the effect of other forces is also apparent. In particular, the peak centered on the evening of March 3 probably did not occur as a direct result of wind activity.

## Seiche Activity

Examination of the tidal data from the bay gage revealed that relatively short period oscillations in the water level frequently occurred. A very large proportion of these oscillations had periods of about four hours, and thirty-six well-defined peaks were selected for study. The average period of these fluctuations was 4.16 hours and their amplitude was about 0.05 feet. The range in periods was between 3.5 and 5.5 hours, but twenty-one of these periods were between 4.0 and 4.3 hours.

East Matagorda Bay is composed of a long, roughly rectangular basin of almost constant depth surrounded by a narrow, shallow shelf between the basin and shore. If standing waves are developed along the length of the deeper basin, then a theoretical period of oscillation is given by Merian's formula (15) to be

$$T = \frac{2L}{n\sqrt{g\bar{d}}}$$

where L is the basin length (16.7 miles), $\bar{d}$ is the average depth (4 feet) and n is a positive integer representing the number of nodes in the wave pattern. For the parameters given, Merian's formula yields a period of 4.3 hours for first order oscillations. This agrees quite favorably with the 4.16 hour period recorded by the tide gages, and indicates that single node standing waves apparently occur quite frequently in East Matagorda Bay during the winter months.

It is very likely that many of these seiches result from the passage of strong atmospheric frontal systems and associated north winds. Several instances of seiche activity were evidenced during the rapid and substantial lowering of the bay waters associated with these high pressure systems.

The tide records from the inlet gage also indicated abnormal fluctuations in the water surface. Very short-period oscillations of considerable magnitude occurred in the channel, particularly during high water conditions. To investigate this activity in greater detail, a sensitive tide gage was temporarily installed and operated for two one-hour periods during the high tide of March 20. During this time the winds were from the southeast at ten knots and wave action was light, with breakers of about two feet. The tide records obtained are presented in Figure 28.

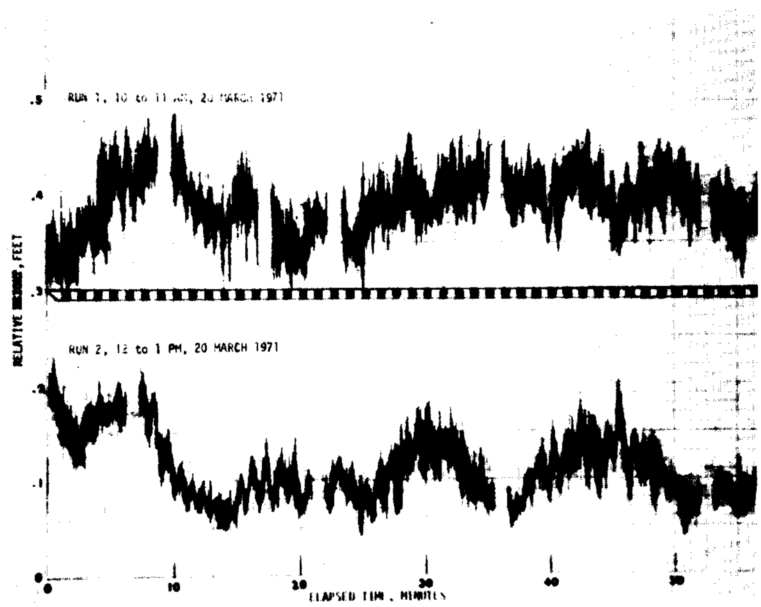



FIGURE 28.--INLET TIDE GAGE RECORD,
20 MARCH, 1971

Two discrete sets of oscillations are indicated: small amplitude (0.4 inches), relatively short period (48.6 seconds) waves are imposed on longer fluctuations of about 15.6 minutes having amplitudes of about 0.9 inches. The shorter period waves are assumed to be remnants of large waves breaking on the bar at regular intervals, although some type of large scale cyclic fluctuation in the water level similar to surf beat cannot be discounted. Periods of observed oscillations at interior spit positions were measured with a stop-watch, and agree quite well with those recorded by the gage. Considering the long period waves, and assuming that the inlet channel is a rectangular basin 6000 feet long and six feet deep, the period of natural oscillations calculated from Merian's formula is found to be 14.5 minutes, which agrees reasonably well with those recorded. The cause of these channel oscillations is unknown, but they occurred during most periods of slack high water.

## Velocity Data

Knowledge of the current velocities through Brown Cedar Cut is important for the determination of the quantities of water exchanged between the bay and gulf, as well as for the prediction of scour and deposition of sediment in the channel. To determine the velocities from tidal differential data, Manning's equation for uniform turbulent flow through a straight prismatic channel was considered. The average velocity, V, in the channel is given by:

$$V = \frac{199\ h^{2/3}\ S^{1/2}}{n}$$

where L is the channel length, ΔH is the tidal differential, S is the slope of the water surface (ΔH/L), R is the hydraulic radius of the channel at mean water level, and n is Manning's coefficient, a measure of the channel roughness. In applying this equation to the inlet conditions, the following assumptions were made:

1. The tidal fluctuations at the inlet mouth are closely approximated by those recorded at the inlet tide gage.
2. The entire surface of East Matagorda Bay responds uniformly to the incoming and outgoing tide. Thus, the elevation of the water at the bay end of the main channel is assumed to be identical to that recorded at the bay gage.
3. The channel is straight and prismatic, having a length of 6000 feet, a cross-sectional area of 2480 square feet, and an hydraulic radius of 4.43 feet.
4. Flow is uniform, thus neglecting accelerations due to the rate of change of the tidal differential.
5. The value of Manning's coefficient for the channel is 0.02, corresponding to a description of channel roughness characteristics given by Chow (12).

Substituting the values for the conditions at Brown Cedar Cut, the average instantaneous velocity is found to be $V = 2.6 \sqrt{\Delta H}$. Applying this relationship to the previously determined tidal differential data, the time history of the current velocity was computed, and is presented in Figure 29. The inclusive dates of these records were selected to correspond to the periods between the topographic surveys discussed later. Selected velocity characteristics obtained from this record are presented in Table 2.

Considering the large number of assumptions required for the use of Manning's equation, it was considered desirable to compare the theoretical velocities with experimentally determined values. Therefore, a twenty-five hour velocity measurement study was performed on March 4 and 5, 1971. A detailed description of this investigation and results obtained are presented in APPENDIX.-CURRENT MEASUREMENTS. To compare the experimentally determined values with those given by Manning's formula, the measured average velocities were plotted against $\sqrt{\Delta H}$ in Figure 30. A straight line was best-fitted between the data points, and was found to have a slope of 2.65. This indicates remarkable agreement with Manning's equation value of $2.6 \sqrt{\Delta H}$. However, the line crosses the vertical axis at a velocity value of 0.5 feet per second, indicating that a flood current of this magnitude was imposed on the hydraulic currents. The origin of this additional component is unknown, but it may result from the transport of water into the inlet by littoral

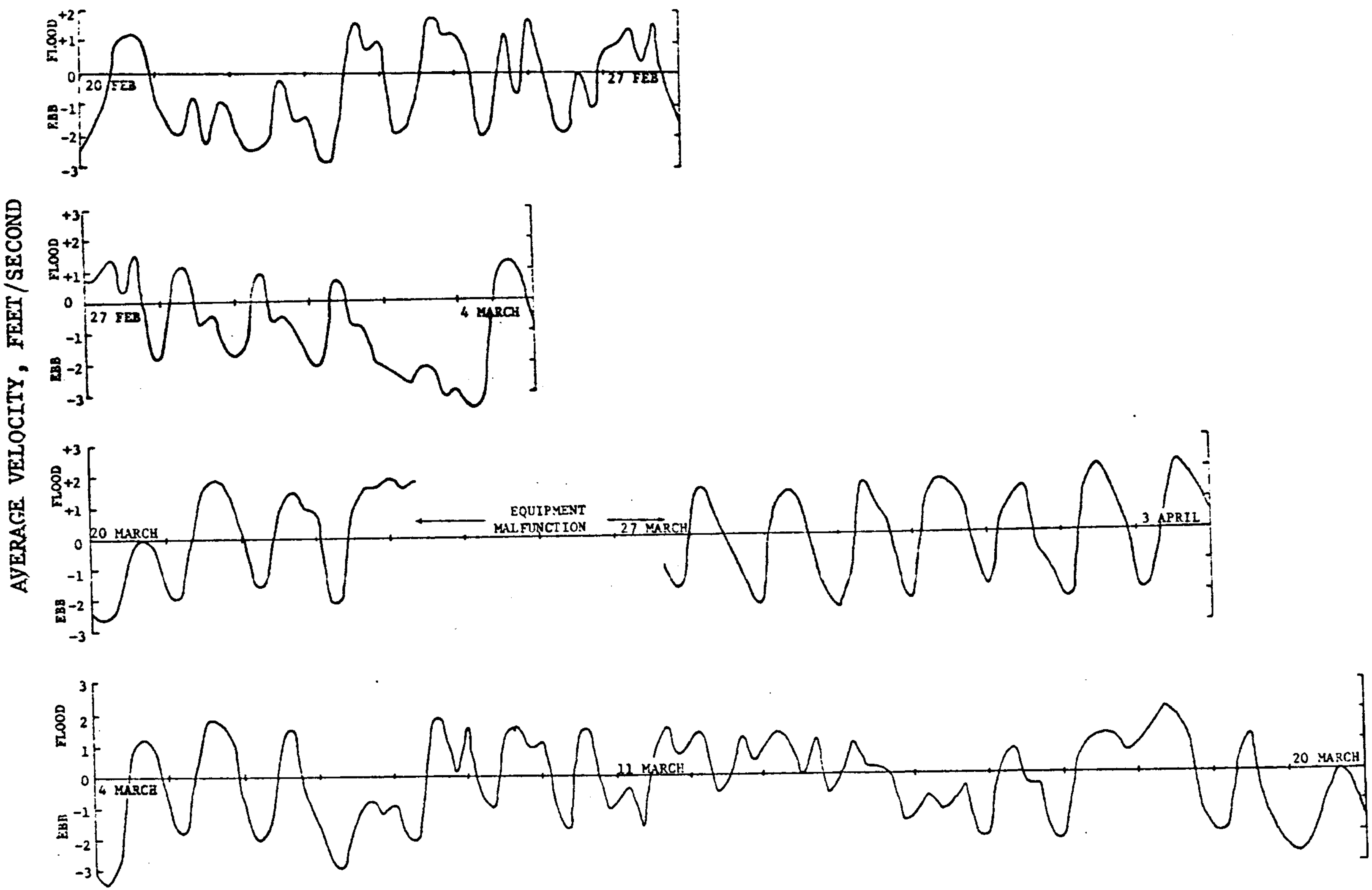



FIGURE 29.--COMPUTED TIDAL CURRENT VELOCITY, 20 FEBRUARY THROUGH 3 APRIL, 1971

| Tidal Current | Velocity, Feet/Sec | | Per Cent of Time | | | |
|---|---|---|---|---|---|---|
| | $V_{max}$ | $V_{average}$ | Current Direction | V>1.8ft/sec | V>2.2ft/sec | V>2.6ft/sec |
| Flood | 2.2 | 1.1 | 44 | 1.6 | 0 | 0 |
| Ebb | 3.5 | 1.5 | 56 | 14.0 | 7.3 | 3.0 |

TABLE 2.--VELOCITY CHARACTERISTICS AT BROWN CEDAR CUT, FEBRUARY 1 TO APRIL 9, 1971

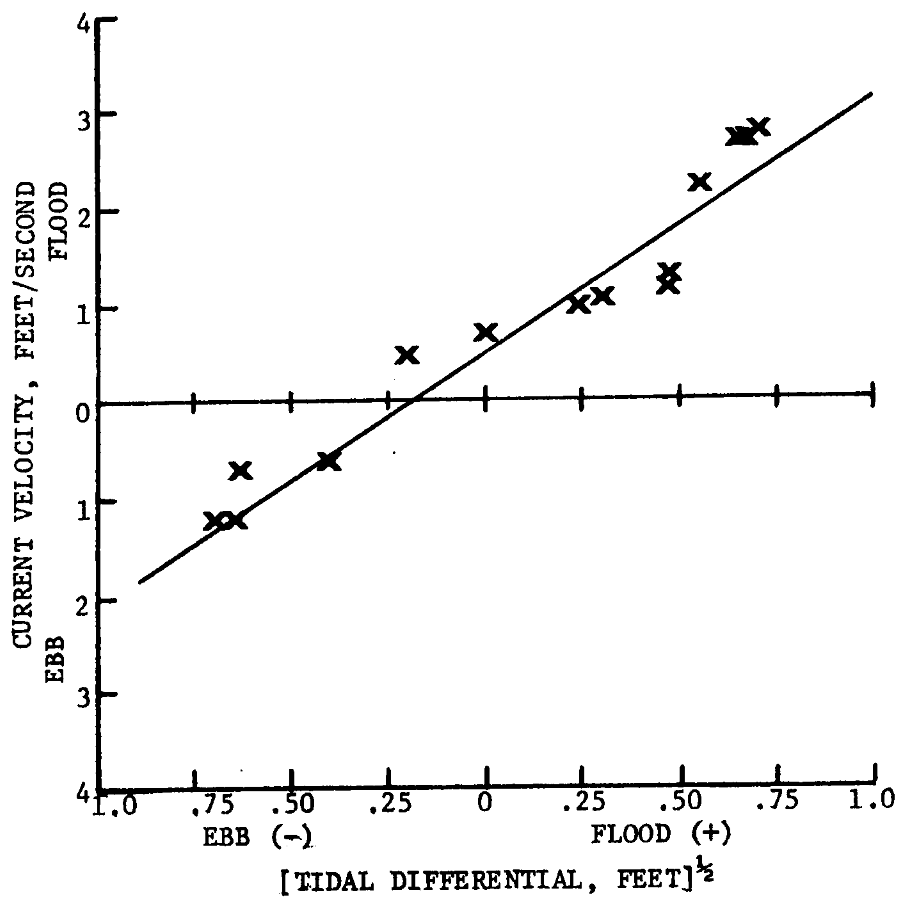



FIGURE 30.--OBSERVED CURRENT VELOCITY VS. TIDAL DIFFERENTIAL

currents or wave action. Breaking wave heights were about four feet and longshore current velocities were in the order of 1.5 feet per second during the measurement period. Although strong winds were blowing from the southeast, calculations indicate that wind-induced water velocities would be very small compared to currents of hydraulic origin.

It appears that the relation between tidal differential and average velocity can be reasonably well represented by use of Manning's equation, but that during periods of strong wave action an additional flood component should be considered.

## Discharge Characteristics

In the absence of direct current measurements, the quantity of water exchanged between the bay and gulf has been used by some researchers to predict velocities through entrance channels. The average current velocity through Brown Cedar Cut based on the amount of water flowing into and out of the bay is obtained from the following equation:

$$V = \frac{h\ A_b}{T\ A_c}$$

where h is the mean tide range in the bay (0.24 feet), $A_b$ is the horizontal area of the bay ($1.5 \times 10^9$ square feet), $A_c$ is the cross-sectional area of the entrance (2480 square feet), and T is the tidal period, assumed to be about twenty-five hours. This equation yields an average flow velocity through Brown Cedar Cut of 1.60 feet per second, based on a tidal prism in East Matagorda Bay of $3.6 \times 10^8$ cubic feet. The equation gives a higher value than the 1.26 feet per second determined from tidal differential data. The increase may be ascribed to the fact that not all water enters the bay through the inlet. The north side of the bay is, for the most part, separated from the Intracoastal Waterway by large spoil banks. However, ten gaps in the banks do exist through which water could be exchanged. Most of these are quite shallow and probably contribute insignificant amounts of water to the bay, but at Caney Creek cutoff, a depth of about six feet has been maintained. Calculating the quantity of water required to produce an average velocity of 1.26 feet per second, and subtracting it from the previously determined tidal prism, indicates that about $0.8 \times 10^8$ cubic feet enter the bay from sources other than the inlet. Therefore, velocities through the inlet should be based on an adjusted tidal prism of $2.8 \times 10^8$ cubic feet.

Another method to determine the applicability of velocity determinations based on discharge rates entails the use of data obtained during the twenty-five hour velocity measurement study. Figure 69 of APPENDIX.-CURRENT MEASUREMENTS contains a time history of the instantaneous rate of discharge, and integrating this curve with respect to time yields the total amount of water which passed through the inlet between the time limits of integration. Comparison of these values with quantities obtained by computing the product of the bay area and the corresponding water level increases is presented in Table 3. The values presented indicate that the quantitites obtained using an estimated tidal prism greatly exceed those observed. This can be explained in two ways. First, with the substantial reduction in bay water elevations due to the strong north wind, a proportionately larger amount of the inflow may have been introduced by way of the Intracoastal Waterway. The long-term velocity data indicates a definite predominance of ebb flow between February and April. This tends to verify the fact that significant quantities of water enter the bay from the Intracoastal Waterway. An additional possibility is that there was a large discrepancy between the increases in water elevation at the eastern and western ends of the bay. Considering the flow entering the bay at Brown Cedar Cut, it seems very unlikely that the bay water surface would have risen uniformly in response to the inflow. Rather, the east end would have shown a maximum water surface rise, with decreasing values toward the west. Such action would result from the significant friction effects associated with the unusually shallow east end.

Considering the discrepancies discussed above, it is felt that a representative concept of flow characteristics can be obtained only through an accurate and comprehensive velocity or tidal differential measurement program. Use of the tidal prism to

| Tidal Current Condition | Total Discharges: Observed ($Q_o$) | Total Discharges: From Tidal Data ($Q_T$) | $Q_T/Q_o$ |
|---|---|---|---|
| Flood, 4 March | $+1.0\times10^{8}$ | $+7.5\times10^{8}$ | 7.5 |
| Ebb, 4-5 March | $-6.1\times10^{7}$ | $-3.3\times10^{8}$ | 5.4 |
| Flood, 5 March | $+2.7\times10^{8}$ | $+5.4\times10^{8}$ | 2.0 |

TABLE 3.--COMPARATIVE TOTAL DISCHARGES, EAST MATAGORDA BAY, MARCH 4 AND 5, 1971

estimate discharge quantities does not lend itself to accurate portrayal of the relationship between East Matagorda Bay and Brown Cedar Cut.

## Bottom Shear Stress

Of prime importance in establishing the stability of a natural inlet is the knowledge of the flow characteristics associated with the initial transport of bottom material. However, the processes of incipient motion are statistical in nature, and there is no discrete condition at which motion begins throughout the channel. Rather, the first manifestation of bed movement is the occurrence of individual gusts of sediment motion, randomly distributed in time and space. Therefore, "critical conditions" may vary over a wide range of flow regimes, depending upon the interpretation of the observer. To minimize subjective analysis in a study of critical conditions, the following three criteria established by Kramer (29) were considered:

1. Weak movement indicates that a few or several of the smallest sand particles are in motion in isolated spots in small enough quantities so that those moving on one square centimeter of the bed can be counted.
2. Medium movement indicates the condition in which grains of mean diameter are in motion in numbers too large to be countable. Such movement is no longer local in character. It is not yet strong enough to affect bed configuration and does not result in appreciable sediment discharge.
3. General movement indicates the condition in which sand grains up to and including the largest are in motion and movement is occurring in all parts of the bed at all times.

A discussion of these criteria and related studies is presented in (57).

Early investigators attempted to relate critical conditions to characteristic bottom velocities, e.g. scour velocity. However, Graf (19), in a review of scour criteria, concludes that uncertainties in the definition and determination of bottom velocity make use of this parameter questionable. A more accurate representation of critical conditions is obtained through the use of the critical shear stress or tractive force, $\tau_c$. Investigations by Shields (51) and others have resulted in a widely accepted relationship between the critical shear stress, median sand size, and related flow parameters. However, in considering the bottom sediment at Brown Cedar Cut, it was felt that experimental determination of critical conditions would enhance the accuracy of stability predictions. Therefore, laboratory tests were performed in a forty foot flume, eight inches wide. A horizontal sand bottom four inches thick was covered with nine inches of water, and currents were generated over this bed. The median sand diameter was 0.17 millimeters. Velocity profiles at one-twentieth of a foot intervals were obtained using a Leopold & Stevens midget current meter. Two profiles were measured for each of Kramer's critical conditions to insure accuracy.

Determination of the critical shear stress was made by the application of the Prandtl-von Karman universal velocity distribution law for fully developed turbulent flow (12):

$$U = 2.5\ U^*_c \ln \frac{y}{y_o}$$

where U is the velocity at a depth y, $U^*_c$ is the critical shear velocity ($\sqrt{\frac{\tau_c}{\rho}}$), and $y_o$ is the depth at which the velocity reaches zero. From the velocity profiles obtained for each condition, the following values of critical shear stress were determined:

| Condition | Critical Shear Stress $lb/ft^2$ | Mean Velocity ft/sec |
|---|---|---|
| Weak Movement | .02 | .84 |
| Medium Movement | .03 | .96 |
| General Movement | .055 | 1.13 |

Comparing these to the value of .0036 $lb/ft^2$ predicted by the Shields relationship, it is seen that the observed values are approximately ten times greater. The reason for such a wide discrepancy is not fully understood, but the observed values approximate that given by Lane for stable channels in sand of this size, .025 $lb/ft^2$ (31).

In applying the results of this study to prototype conditions, it seems reasonable to assume that the value of critical shear stress required for channel stability may in fact be higher than those determined for weak and medium movement, since observed irregularities in the bottom configuration tend to increase shear stress values. Therefore, a critical shear stress of .055 $lb/ft^2$ corresponding to that of general movement will be assumed to represent stable conditions at Brown Cedar Cut.

Values of actual shear stress in the inlet were obtained from velocity profiles taken on March 4 and 5, and are presented in Table 4. The data exhibit relatively good agreement with those obtained in the laboratory, and indicate that less-than critical values of shear stress predominated over the measurement period.

| Time | Shear Stress Pounds/Square foot | Mean Velocity Feet/Second |
|---|---|---|
| 4 March, 1605 | .028 | 1.29 |
| 1735 | .033 | 1.05 |
| 2110 | .048 | 0.85 |
| 5 March, 0100 | .023 | -0.93 |
| 0550 | .011 | -0.80 |
| 0745 | .009 | 0.44 |
| 1000 | .121 | 2.18 |

TABLE 4.--OBSERVED SHEAR STRESS, MARCH 4 AND 5, 1971

## TOPOGRAPHIC CHARACTERISTICS AND MODIFICATIONS

One of the more significant aspects of the study was the determination of factors influencing the shape, size, and stability of Brown Cedar Cut. Therefore, a comprehensive survey of the area was performed in October, 1970, to accurately map the inlet contours and obtain other information useful in the planning of future surveys. Beginning on February 20, 1971, and at approximately two week intervals thereafter, similar surveys were made of the shallow inlet areas and beach contours to delineate changes in the inlet position. A permanent concrete marker was installed on each side of the inlet for control purposes. Subsequent investigation revealed a U. S. Coast and Geodetic Survey triangulation station located in high grass approximately 1500 yards east of the east marker and about twenty yards behind the dune line. The exact elevation of this station is unknown, but it is 4.21 feet above the mean water level established herein. The locations of these markers were presented in Figure 24. Beach and shallow water elevations were determined using a plane table, aledaide, and transit, and selected cross-channel profiles were obtained using an Automation Industries Ultrasonic Distance Meter, Model 1054. Results of these surveys are presented in APPENDIX.--TOPOGRAPHIC SURVEY DATA. Topographic information obtained from the surveys was employed in the analysis of the inlet's response to coastal processes using the method outlined below.

Local contours of the mean water level were drawn for each pair of consecutive surveys. From these figures the character of the inlet changes during the period between surveys was delineated. To provide additional insight into the nature of these changes, four elevation profiles on each side of the inlet were constructed for the months of October, March and April. The locations of these profiles are presented in Figure 31, and the profiles are illustrated in Figures 32 through 35. Both types of comparisons proved useful in determining the total amount of sediment deposited or removed from the area.

Determination of environmental conditions prevailing during the periods between surveys was of critical importance. Strong currents or wave action can produce drastic short-term changes in inlet geometry. Current velocities predicted from tidal differences were presented previously in Figure 29. Observations of wave conditions were available only for brief periods, so an indirect method for determining the nature of the wave activity between surveys was employed. Although wave characteristics are not always proportional to wind direction and magnitude at the site, it was felt that a reasonable estimation of wave action could be made from a knowledge of wind characteristics. Therefore, wind regimes at the inlet were estimated from wind data obtained from the National Oceanic and Atmospheric Administration for Freeport and Port O'Conner. Wind observations taken at six hour intervals

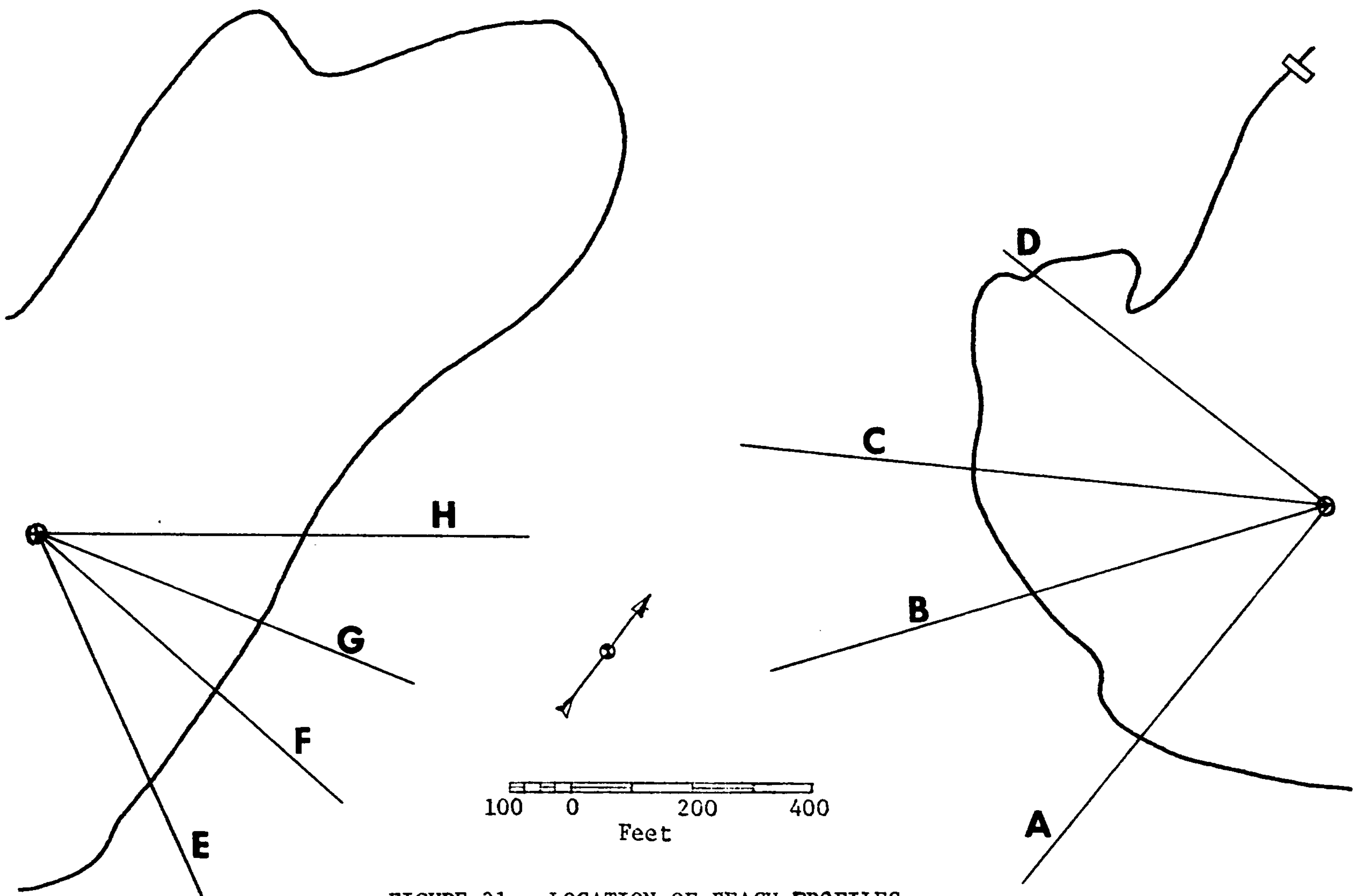



FIGURE 31.--LOCATION OF BEACH PROFILES

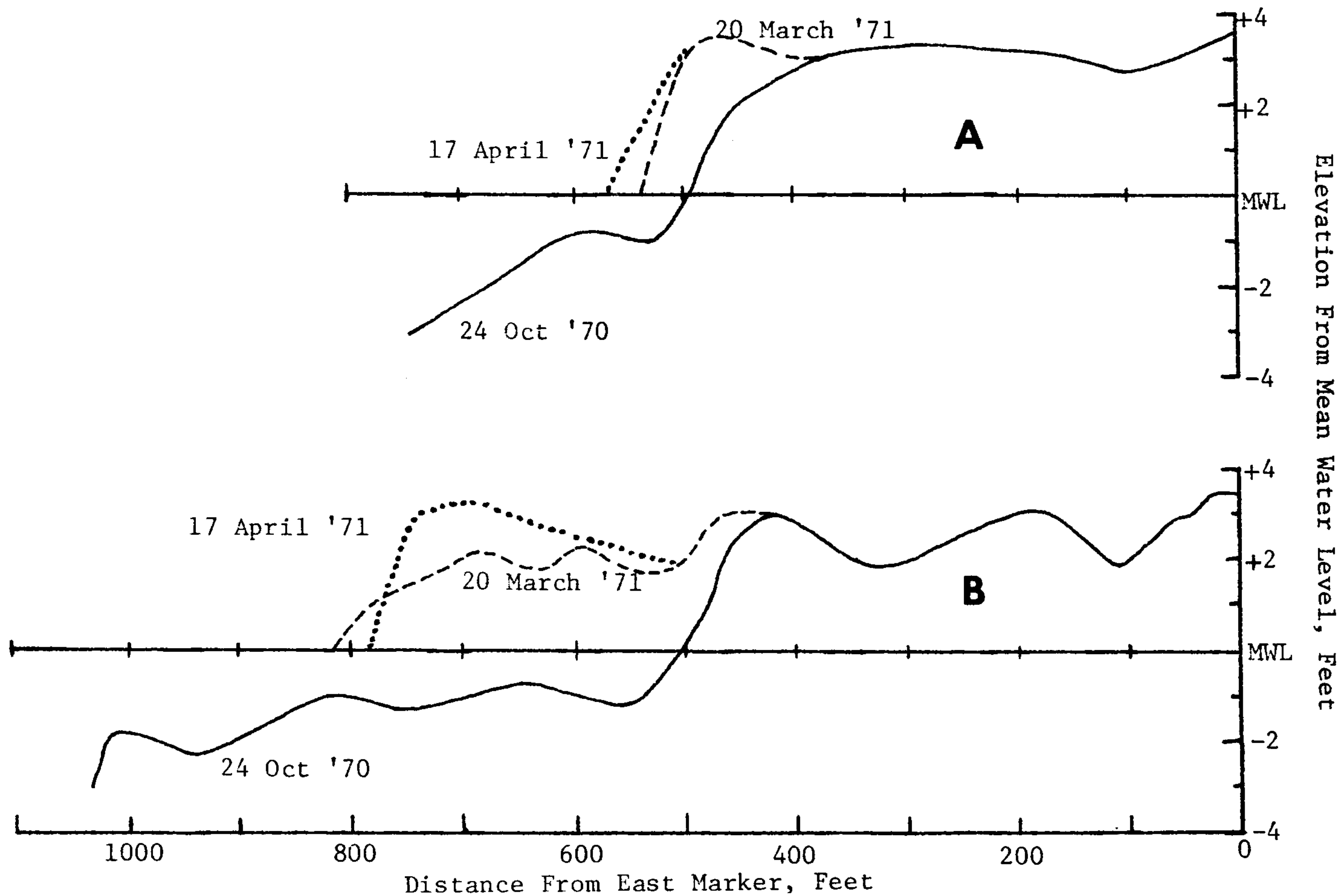



FIGURE 32.--EAST SPIT BEACH PROFILES A AND B

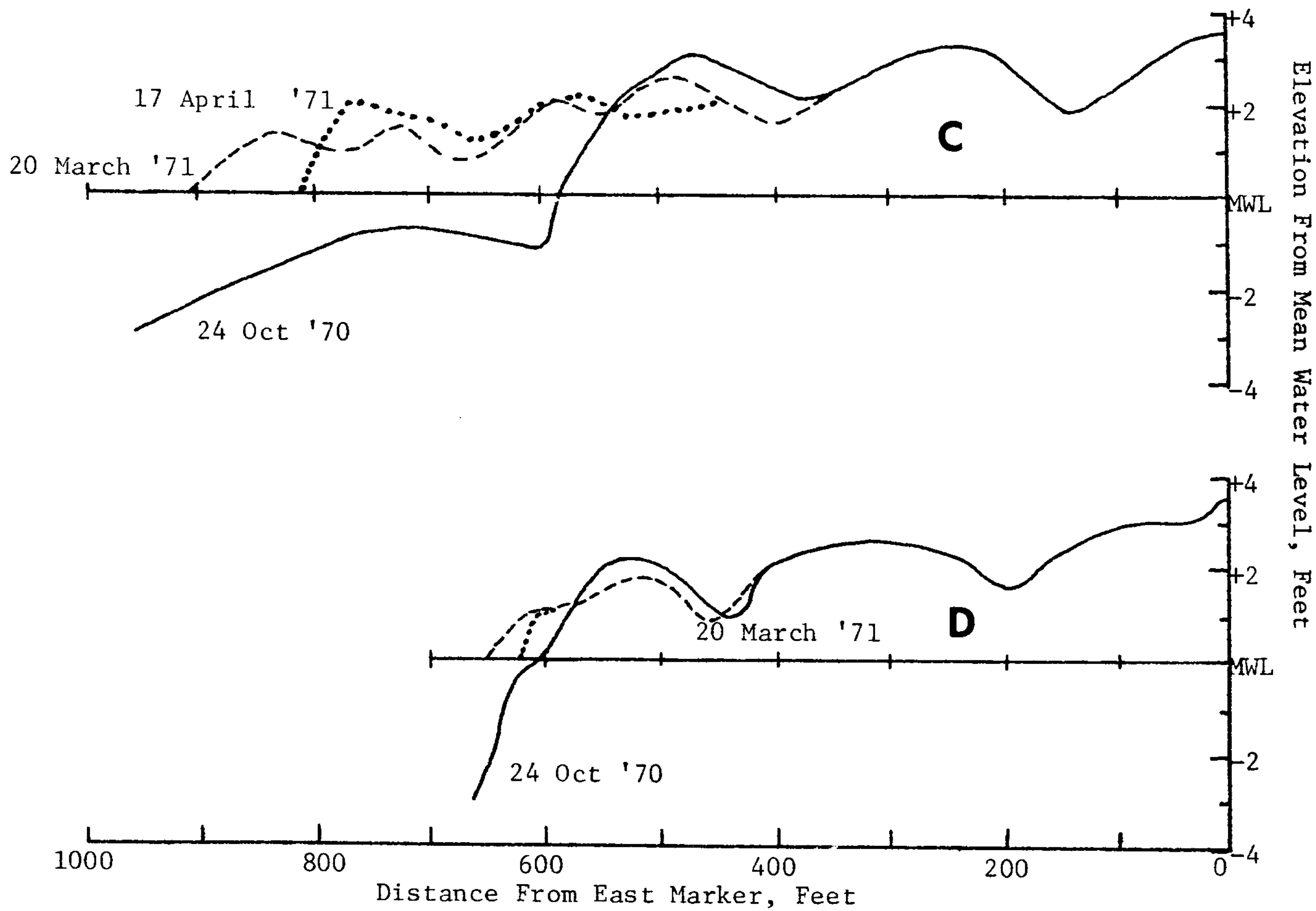



FIGURE 33.--EAST SPIT BEACH PROFILES C AND D

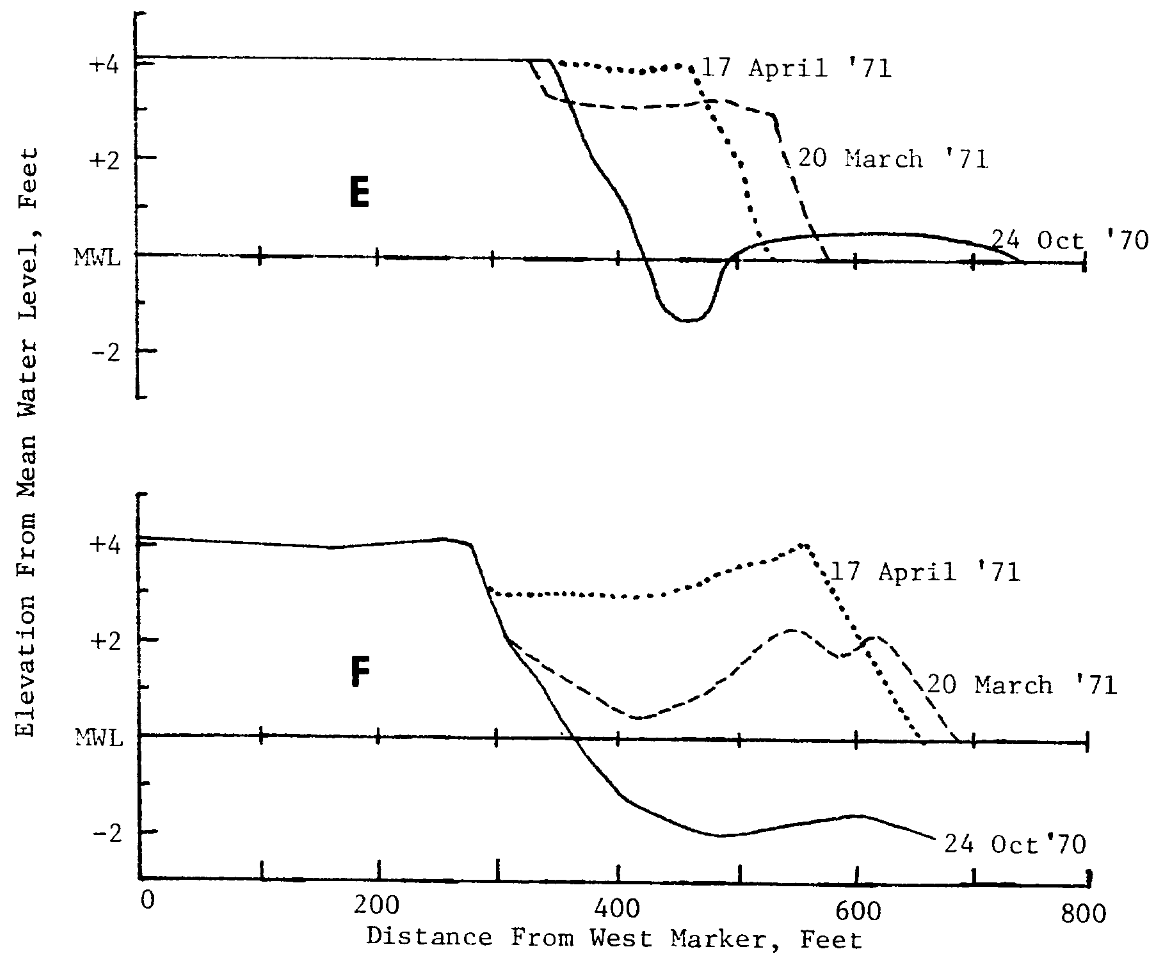



FIGURE 34.--WEST SPIT BEACH PROFILES E AND F

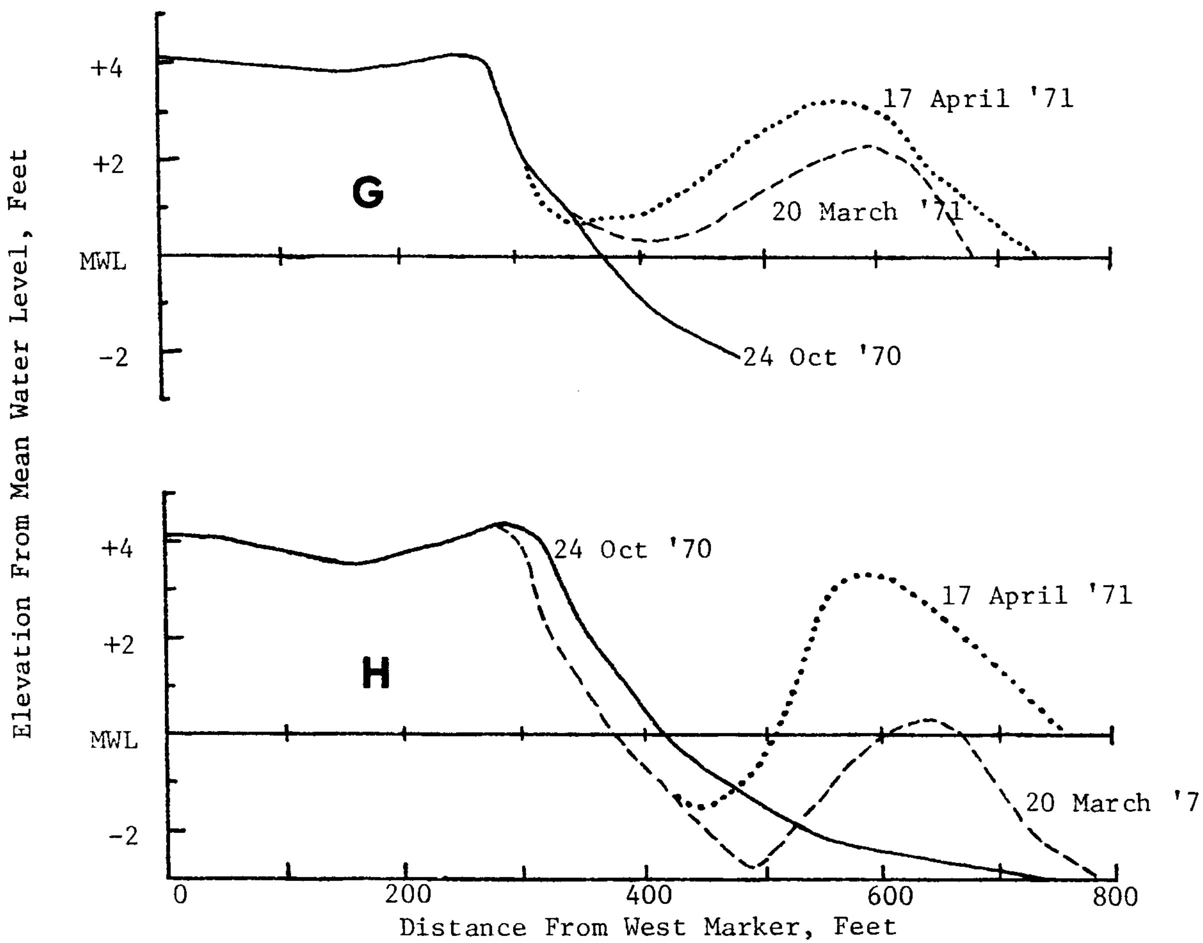



FIGURE 35.--WEST SPIT BEACH PROFILES G AND H

and occurring between survey dates were first sorted according to direction--those having a strong north component, i.e. north, north-northwest, and north-northeast, were grouped together as north. Similar groups were established for east, south, and west. Winds from the northeast, southeast, southwest, and northwest formed four other groups of wind velocity observations. Each group was then summed, and these sums were divided by the number of days in the observation period. The resulting values are daily averages of the relative forces of prevailing winds. Computations were performed for each survey interval and plotted in the form of a wind force rose on the corresponding shoreline comparison figure. A detailed discussion of the nature and probable causes of changes in inlet geometry is presented below in chronological order.

October 24: The general configuration of the inlet and prominent reference points are indicated in Figure 36. The distance between shorelines at the mouth was about 1450 feet, but wide shoal areas extended outward from the banks, and the portion of the channel greater than six feet deep was only about four hundred feet wide. The positions of the concrete reference markers are indicated, as well as the sites of two beach houses and a boat dock. The weathered remains of spoil banks deposited during the futile dredging attempt in 1964 are also included. The inlet exhibited the typical north-south orientation of other Texas inlets (44) and the main channel followed a winding path through interior

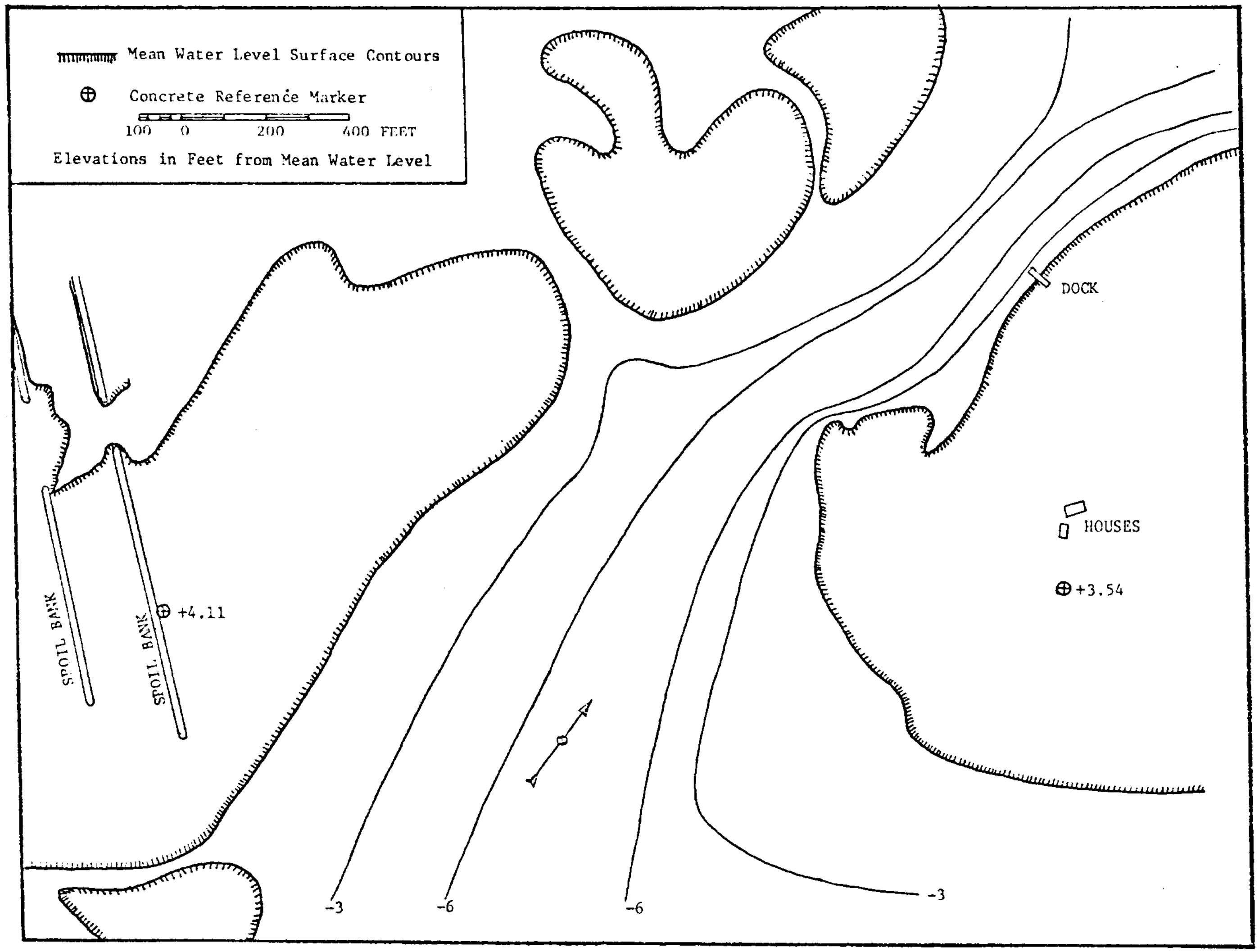



FIGURE 36.--BROWN CEDAR CUT LOCATION CHART, 24 OCTOBER, 1970

islands to the bay. The east side of the inlet was a sand spit that exhibited a well defined "hook" configuration. The origin of hooked spits was reported by Evans (17), who concluded that they form as a result of wave refraction around the spit end. However, Evans' findings require that for growth of such structures, waves must approach the spit obliquely from the mainland or upcoast side, in this case from the east or southeast. Waves approaching normal to the beach or from a southerly direction will not transport sand to the spit end, and may in fact actively erode the spit area. The converse is true for the west spit; growth due to wave refraction will occur only when waves strike the beach with a predominately south or west component. In both cases, however, refraction of offshore waves by the adjacent gulf shoals may cause local directional variability.

The mechanism of growth by wave refraction was observed in January on the east spit. Constructive interference of waves breaking on the shoals produced a series of small amplitude waves which traveled over regions of the spit just barely covered with water. The waves had periods of about forty-five seconds and resembled small tidal bores about two inches high. In passing over the shallow bottom the wave fronts kicked up small shells, pebbles, and sand. As material was suspended by the front, the remainder of the wave transported it along the spit. Upon reaching the deeper water at the end of the hook, most of the sand was deposited, but some remained in suspension to be deposited on the back side of the hook.

October 24 to February 20, Figure 37: The first presentation of shoreline comparisons indicates significant spit growth on both sides of the inlet in the four month interval. Wind activity during this period was moderate and during the months of November and December exhibited a strong northern predominance. Rainfall throughout the period was about two inches below normal (56). Observations of spit contours in December indicated that growth was predictably minor until 1971. Winds in the first two months of 1971, although still moderate for the most part, exhibited a more south and easterly trend, and associated waves would account for deposition on the spits. The eastern hooked spit of October was extended about three hundred thirty feet across the channel by means of a second hook built over the former shoal area by wave refraction. The beach profiles of March 20 in Figures 32 and 33 closely approximate those for February, which provide evidence that a total of 585,000 cubic feet of sediment was accumulated shoreward of the February 20 mean water contour. The migration of the west spit a distance of five hundred thirty-five feet northward is attributed primarily to refraction of southerly waves. However, the effects of tidal currents must also be considered. Velocity data is not available for this period, but early winter storms from the north probably produced significant ebb currents.

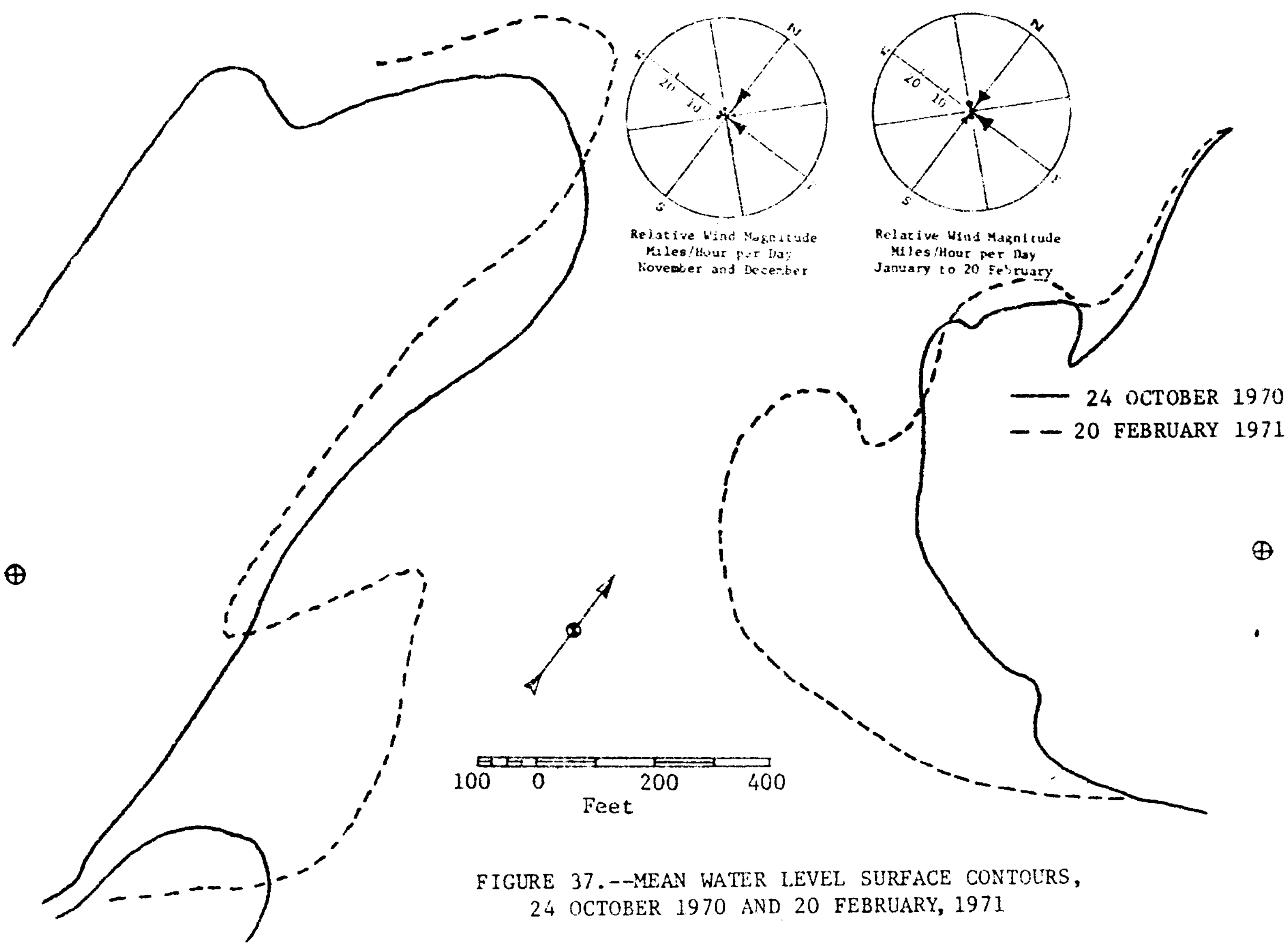



FIGURE 37.--MEAN WATER LEVEL SURFACE CONTOURS,
24 OCTOBER 1970 AND 20 FEBRUARY, 1971

In decelerating over the shoal areas on the west side, these currents may have deposited considerable amounts of sediment eroded from interior locations. The total amount of sand deposited landward of the February 20 mean water contour of the west spit was 391,000 cubic feet.

In contrast to these areas of deposition, substantial erosion of the interior west bank occurred. This is attributed to the inlet's tendency to maintain a stable channel cross-section. In response to encroachment by the east spit, the main channel migrated westward, and tidal currents were probably responsible for both the erosion of the west bank and its growth toward the north.

February 20 to 27, Figure 38: During this period the second hook on the east spit was modified considerably. Predominate wind direction was from the east, and deposition occurred along the entire southwest edge. Wave activity on the 27th was of great magnitude and almost directly from the east, and a southwestward flowing longshore current of over three feet per second was measured near the inlet. Current velocities during this period showed a strong predominance for ebb flow resulting from the passage of a frontal system on the 21st, which depressed the bay waters for over three days. Therefore, wave refraction patterns were modified by the outward flowing water during that time. Although not exhibiting a hook configuration, a considerable area of the west end of the spit did experience growth, as indicated by the cross-

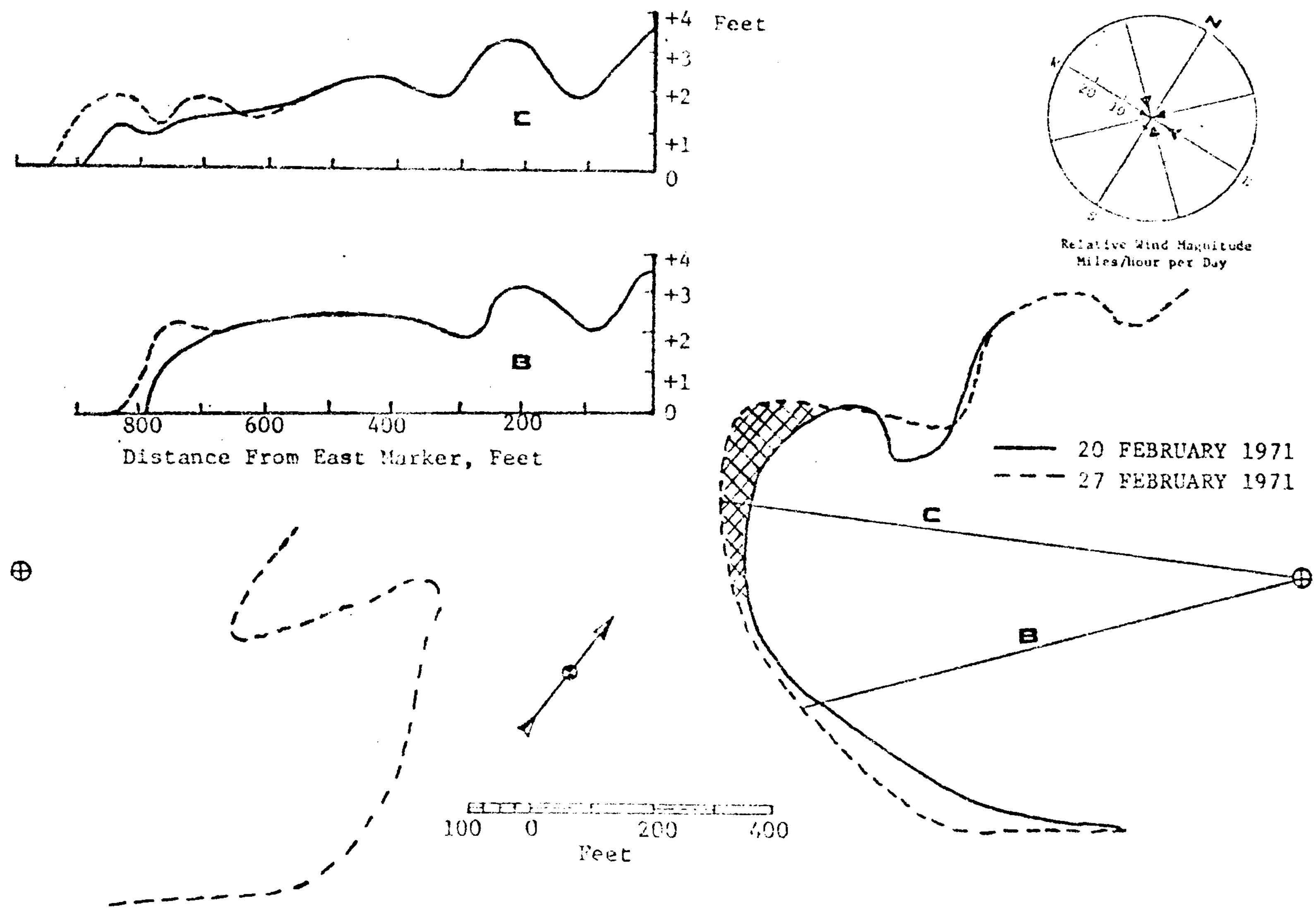



FIGURE 38.--MEAN WATER LEVEL SURFACE CONTOURS, 20 AND 27 FEBRUARY, 1971

hatching in Figure 38. Investigation of beach profiles provided evidence that a beach ridge grew rapidly between the 20th and the 27th, as indicated in the profiles of Figure 38. Yasso, in a comprehensive analysis of spit-building processes, found that one way in which such ridges were formed was by the landward migration of small bars originating below mean low water (59). However, beach ridge formation in this manner required considerably longer than the seven day growth period exhibited at Brown Cedar Cut. Therefore, a more rapid method of ridge formation was considered. King (28) and Wiegel (58) outline a process of berm or ridge building which results in changes identical to those observed. Waves carrying sediment run up the beach face and, as their energy is dissipated by gravity, friction, and percolation, deposit material along the slope. Hayes (22) reports a large ridge built in such a manner at Padre Island, Texas, due to low, long-period hurricane waves, and laboratory studies with Texas beach sand by Chesnutt and Schiller (11) reported development of such a swash ridge. However, it appears that one requirement for this process is that the water level remain rather constant. Examination of tidal records for the period indicated that semi-diurnal gulf tides prevailed between the 25th and the 27th. Semi-diurnal tide ranges are significantly less than the mean range, and during this period averaged less than one-half a foot. Wind data indicated that winds from the east and southeast blew continuously from the 24th to the 27th, meaning that the observed wave activity had probably been in effect for some time. All evidence points to rapid building of the west portion of the spit by the process outlined above. Figures 32 and 33 reveal a series of such ridges on March 20, and it was established that periods of relatively small tidal fluctuations coincided with their formation. Thus, it appears that maximum spit growth is associated with intervals of relatively constant sea level and moderate to heavy wave action.

Deposition also occurred at the north end of the spit, where the indentation between the first and second hooks was filled-in. Observation of the process which caused this deposition was made on February 27. As indicated in Figure 73, a low trough curved southeastward behind the beach ridge. High wave activity caused sporadic overtopping of the ridge by run-up, and water flowed down the back side and along the trough, emptying into the inlet at the indentation mentioned. The flow at some points was of sufficient velocity to scour the sand, with resulting deposition at the inlet. This process may also be responsible for deepening the series of troughs developed at later dates. Contours of the west spit for February 20 were based solely on those of February 27, and no comparison was available.

February 27 to March 4, Figure 39: Wind and current activity during this period were dominated by the effects of a strong frontal system which passed through the area on March 2. The maximum absolute value of tidal differential occurred on March 3,

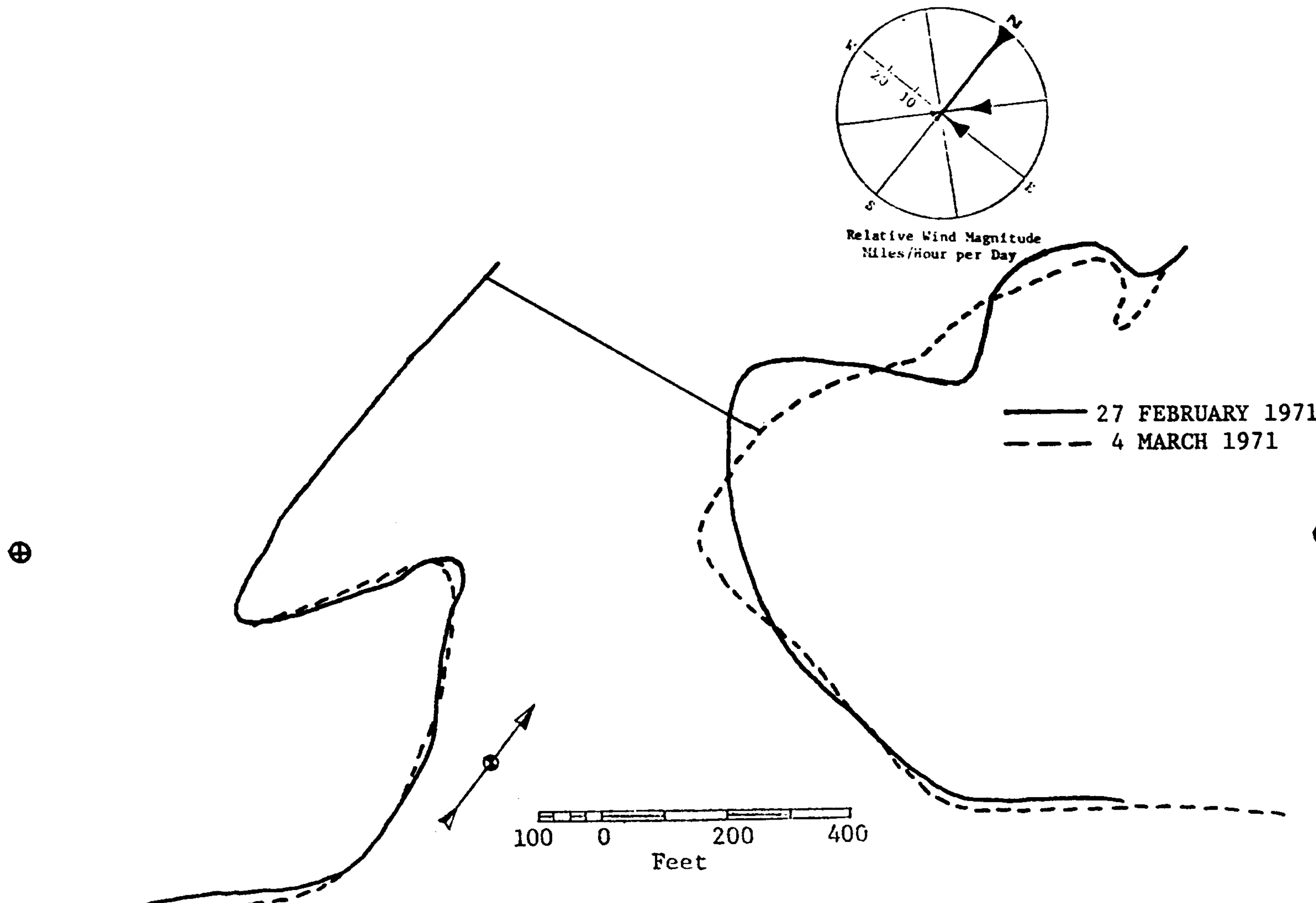



FIGURE 39.--MEAN WATER LEVEL SURFACE CONTOURS, 27 FEBRUARY AND 4 MARCH, 1971

when the bay level was 1.8 feet higher than that of the gulf, producing ebb velocities in excess of 3.5 feet per second. The west spit experienced insignificant modification, and the mean water contours at the southeast corner of the east spit also maintained position. However, the first hook was eroded about twenty feet and the tip of the spit migrated seaward about two hundred feet. Observations of the banks at both locations revealed the existence of small vertical bluffs extending about one foot above the water's edge. Although the exact cause of this erosion is unknown, degradation of the spit end during the morning of March 4 was observed to result from refracted waves from the gulf. However, it is highly doubtful that the extensive erosion experienced at interior locations was due to similar processes. More likely is the possibility that strong ebb currents flowed along the shore and eroded large sections of the banks into the vertical configurations exhibited. Similar structures were observed on February 13, one day after the passage of a rapidly-moving front and associated north winds.

Figure 39 also presents the cross-channel profile measured on March 4 in conjunction with velocity measurements. Note that the gorge closely parallels the east spit shoreline, lending credibility to the theory of erosion by strong currents.

March 4 to 20, Figure 40: Strong winds from the south and moderate flood currents predominated during this period, although

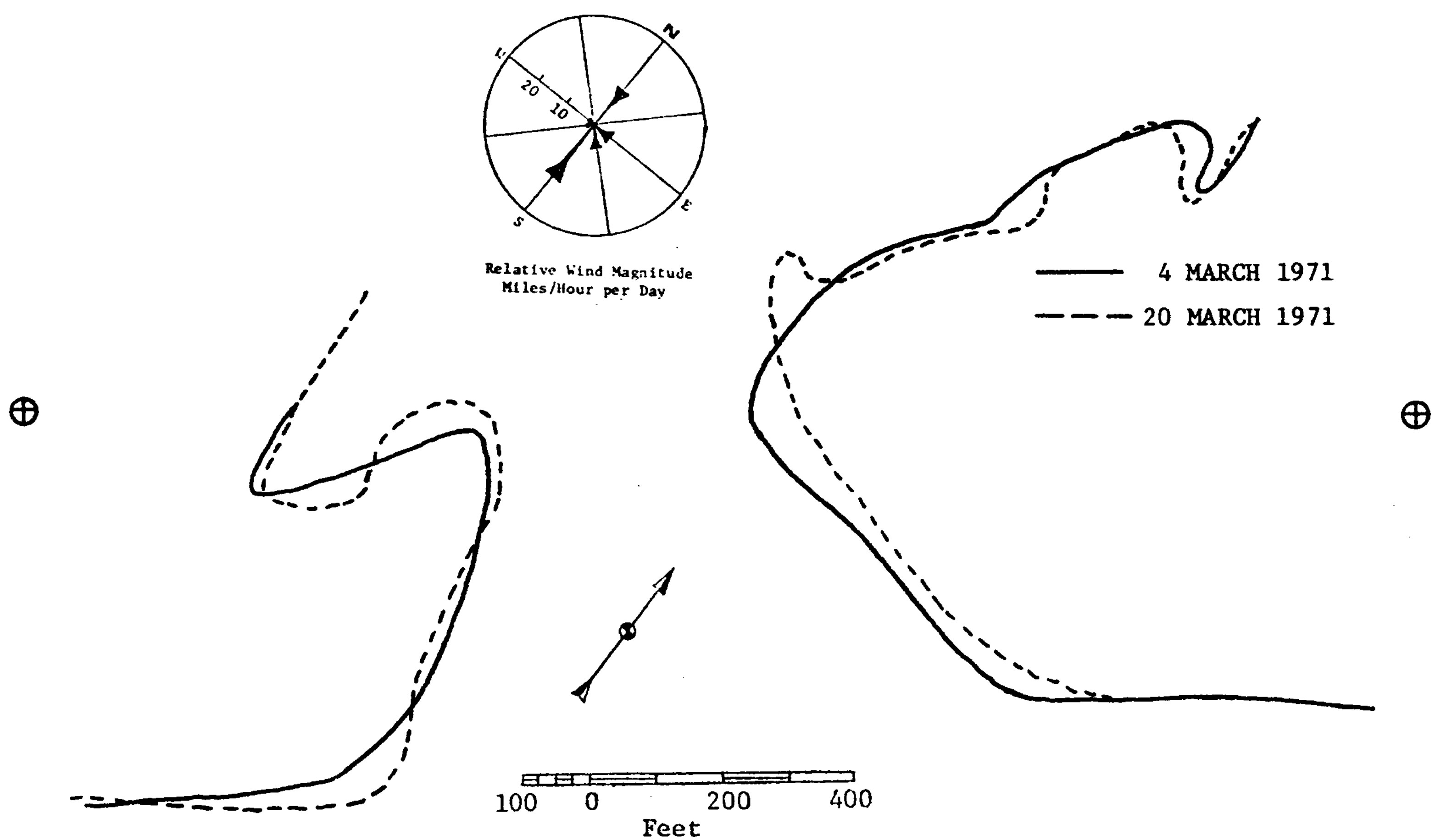



FIGURE 40.--MEAN WATER LEVEL SURFACE CONTOURS, 4 AND 20 MARCH, 1971

the passage of two frontal systems did produce short-term ebb currents of significant magnitude. The inlet apparently responded primarily to wave activity from the south. The west spit acquired a slight bulge at the southeast corner, and built northward, exhibiting a pronounced hooked configuration. Waves and currents moving inward through the channel caused significant degradation of the east bank, but some deposition of this material occurred on the north side.

March 20 to April 3, Figure 41: Diurnal tidal ranges during this period were far above normal, averaging about 1.4 feet. Therefore, current velocities in the order of 1.6 feet per second prevailed, and were about evenly balanced between flood and ebb. Wave conditions were observed at three different occasions during this period and above average breaker heights of about five feet were evidenced each time. Large waves from the south and east, in combination with some of the highest recorded water levels, are assumed to be responsible for the recession of the west spit shoreline. On April 3, waves were observed to be running up the seaward face and frequently overtopped the ridge which formed the backbone of this spit. As the water flowed down the back side, material was transported towards the semi-enclosed waters, where deposition took place. This action, combined with erosion of the seaward face, is believed to have produced the shift in spit location.

Wave action from the east would usually cause cross-channel

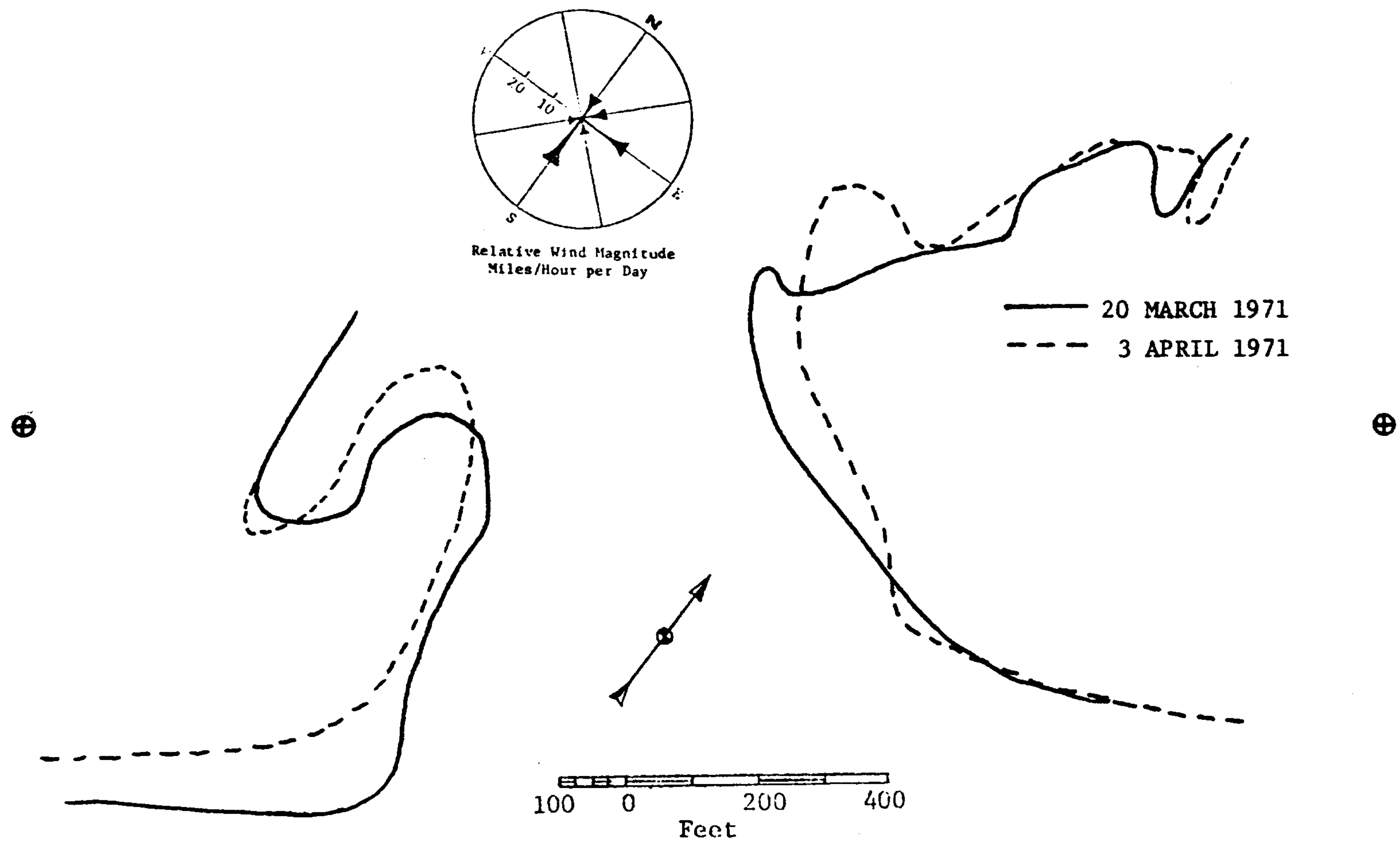



FIGURE 41.--MEAN WATER LEVEL SURFACE CONTOURS, 20 MARCH AND 3 APRIL, 1971

growth of the east spit. However, during this period the only growth experienced was in a northerly direction up the channel. It is theorized that the strong tidal currents, acting in concert with southerly waves, precluded any permanent effects of easterly waves, and in fact actively eroded the east bank. However, the material eroded was apparently transported northward, and subsequent deposition occurred in a pattern characteristic of wave refraction processes, i.e. a well-defined hooked spit.

During this period water levels were so high, and wave action so great, that extensive areas of the barrier island west of the inlet were covered with water. The flow was moving very slowly towards the bay, and provided convincing evidence of the vulnerability of the island to minor increases in sea level.

April 3 to 17, Figure 42: The inlet tide gage unfortunately experienced continued malfunctions, and the computed velocity data was of questionable accuracy. However, it is estimated that current action was about average, with a predominance of ebb flow during the first week. Semi-diurnal tides again occurred in the interim, and growth of beach ridges would therefore be expected. Winds showed a definite southerly predominance, and large waves on the 17th were observed to enter the cut from the south and southeast.

The west spit experienced significant growth in a cross-channel direction as well as a net increase in height. The spit end migrated one hundred thirty-five feet northward and Figures

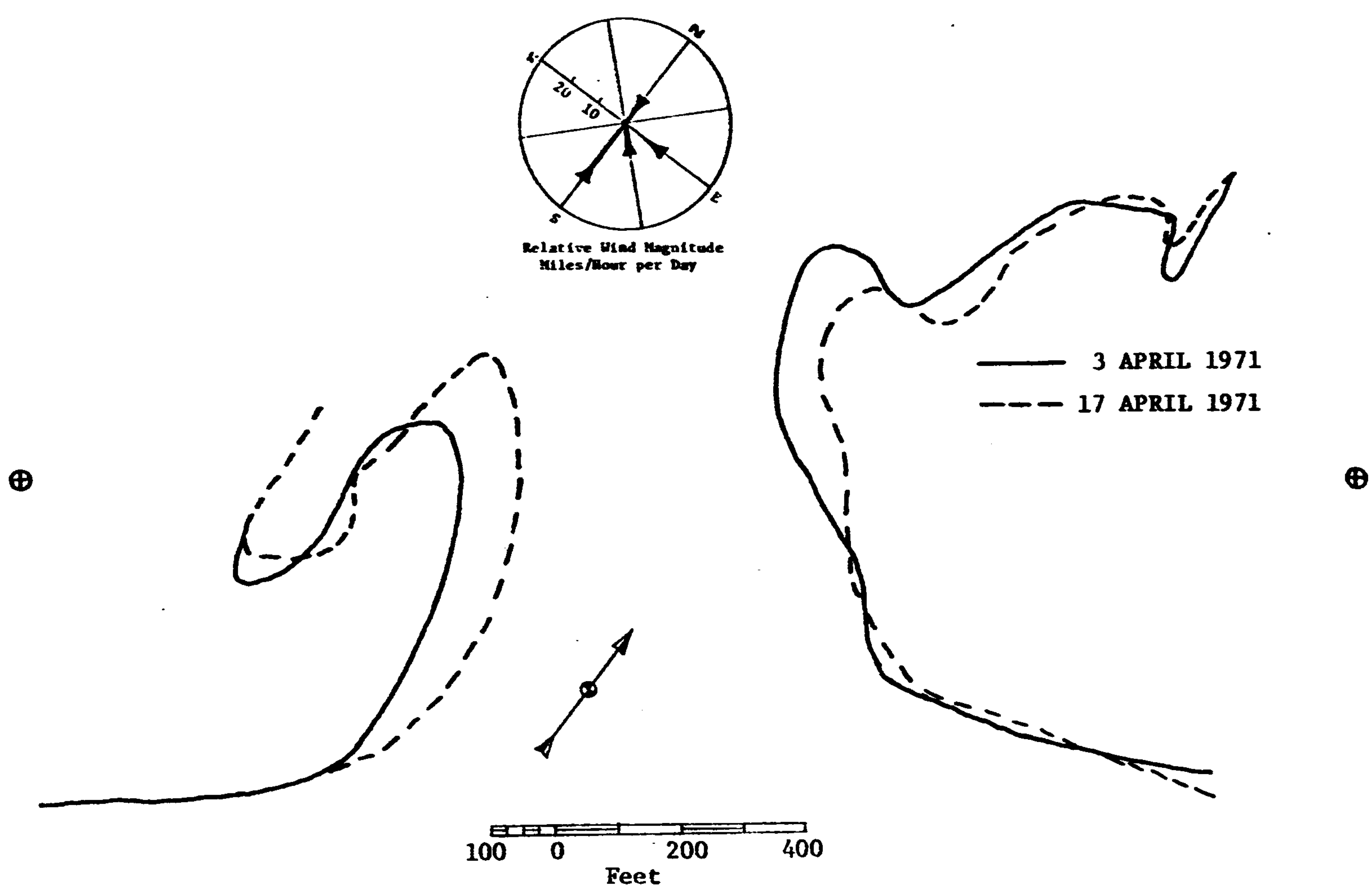



FIGURE 42.--MEAN WATER LEVEL SURFACE CONTOURS, 3 AND 17 APRIL, 1971

34 and 35 reveal that strong wave action added over three feet to portions of the spit topography since March 20. The northward extension was quite localized, for depths in excess of three feet were measured immediately adjacent to the steeply sloping west side.

The east spit experienced degradation of its second hook, apparently due to destructive wave action from the south. However, the prevailing ebb currents may also have contributed to erosion of this promontory. Figures 32 and 33 indicate that only portions of the east spit near Profiles A and B experienced growth between March 20 and April 17. The increase in elevation of over one foot at Profile B resulted from constructive wave action at that point, with significantly less growth occurring at Profile A due to a previously well-established berm.

July 1, Figure 43: A final view of the inlet was obtained from the air, and growth of the west spit in a northerly direction is distinctly evident. The main channel closely skirted this spit, but appears to have turned sharply southwestward a short distance out from the spit. This channel paralleled the shoreline for a few hundred feet before turning once again toward the gulf. Growth of a major shoal area is indicated adjacent to the east spit, and later surveys indicated this region to be exposed at low tide. Thus, it would appear that a new spit was in the process of forming on July 1, parallel to the eastern shoreline but at a considerable distance from the curved portion of the original east spit.

FIGURE 43.--BROWN CEDAR CUT, JULY, 1971
(AUTHOR'S PHOTO)

If such a spit does form, the flow area would be considerably reduced, and it is very probable that closure of the entire inlet would occur within a short time.

## Conclusions

Based on the observed response of Brown Cedar Cut to known environmental conditions, conclusions may be drawn concerning the general nature of future modifications. Analysis of topographic and environmental information revealed that a limited number of typical spit formations were related to discrete combinations of wave and current regimes. This relationship is best described in pictorial form, as presented in Figure 44. Thus, prediction of inlet modifications can be made from a knowledge of previous environmental data. Conversely, observed changes in the inlet configuration allow hindcasting of wave and current activities.

The influence of two additional natural forces on the topography must be considered. First, movement of beach sand by strong winds will contribute to changes in the exposed regions of the spit. Examination of the survey data revealed moderate spit modification above the high water mark, which probably resulted from wind action. Large-scale wind erosion is tempered by the existence of vast quantities of oyster and other shells, which enhance the surface stability. In addition to wind effects, the influence of surface runoff and rainfall is very important. Significant amounts of fresh water contributed to the bay can produce substantial differences in elevation between bay and gulf waters. The resulting ebb currents possess a potential for eroding the inlet banks and widening the deeper channels. The only significant rainfall occurred just prior to the survey of October 24, when six inches were reported in a one week interval at Matagorda. On the 24th, rapid ebb currents were observed, but their effect on the inlet topography could not be determined, since previous contours were not available.

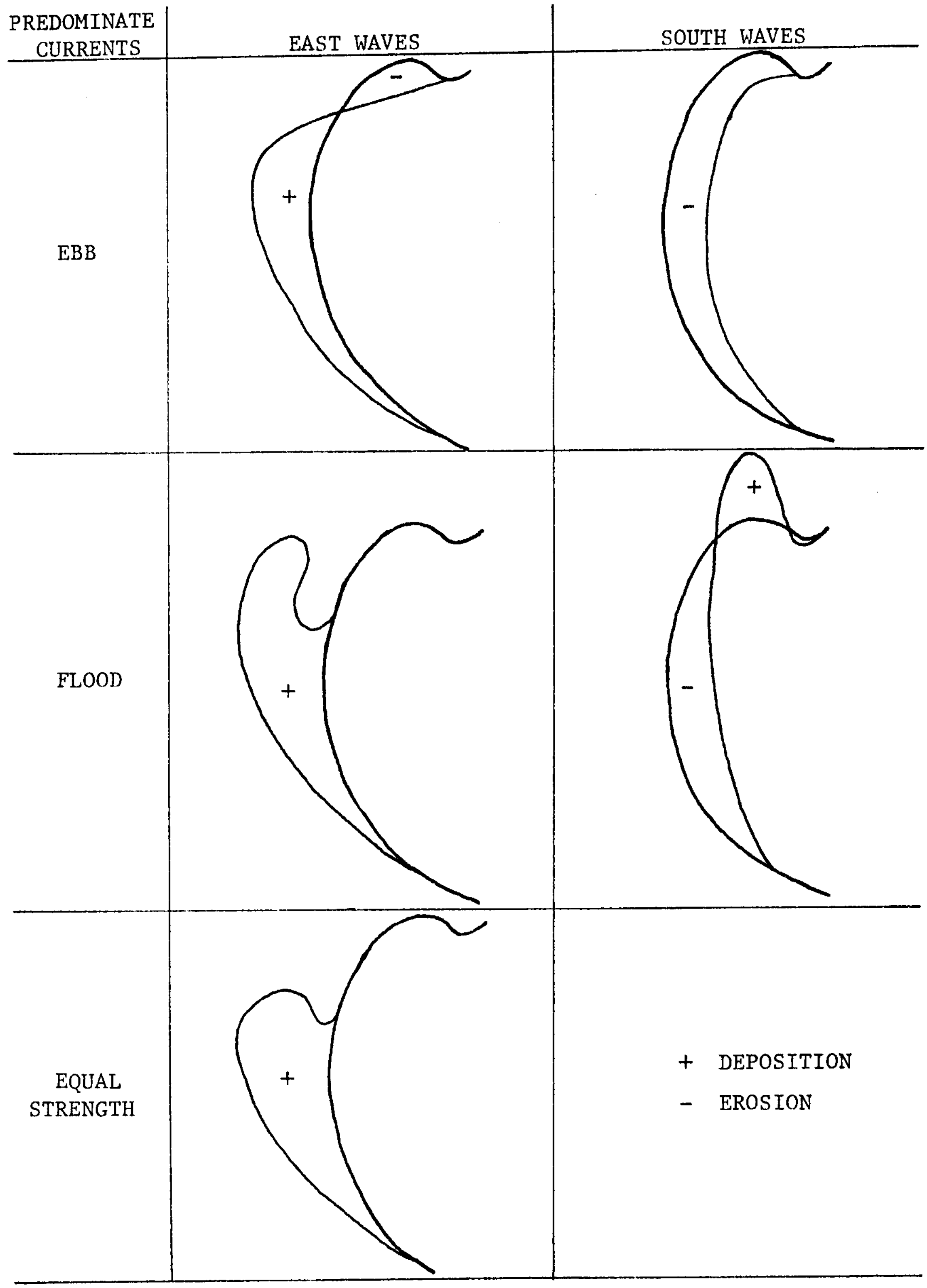



FIGURE 44.--CHARACTERISTIC SPIT MODIFICATIONS

## SEDIMENTARY ANALYSIS

As an aid to delineating velocity patterns in the inlet, and to provide information concerning the channel's sedimentary characteristics, numerous samples of bottom material were collected at Brown Cedar Cut in December, 1970. In shallow water, the samples were obtained by scraping the upper one inch of bottom sand with a small baby food jar. In deeper water, an Ekman grab sampler was employed, but some difficulty was experienced in areas where a shell "pavement" apparently covered the sand. Offshore samples adjacent to the inlet mouth were obtained in April, 1971, from a large cabin cruiser. Again, the Ekman sampler was employed, although some problems were encountered in collecting the finer sediments. Analysis for sample size distribution curves was made using the visual accumulation tube method (13). Central tendencies of the samples were characterized by median diameters in millimeters, and sorting was indicated by use of the phi deviation, $\sigma_\phi$, in accordance with Inman's classification (25).

Figures 45 and 46 present the spacial distribution of sample median sizes and phi deviations. A general trend toward larger median diameters in regions of known high velocity is indicated. In the swash zone and along the gorge banks, where velocity maximums are expected, significant quantities of shell were present and median diameters were large. The finest sediments were found

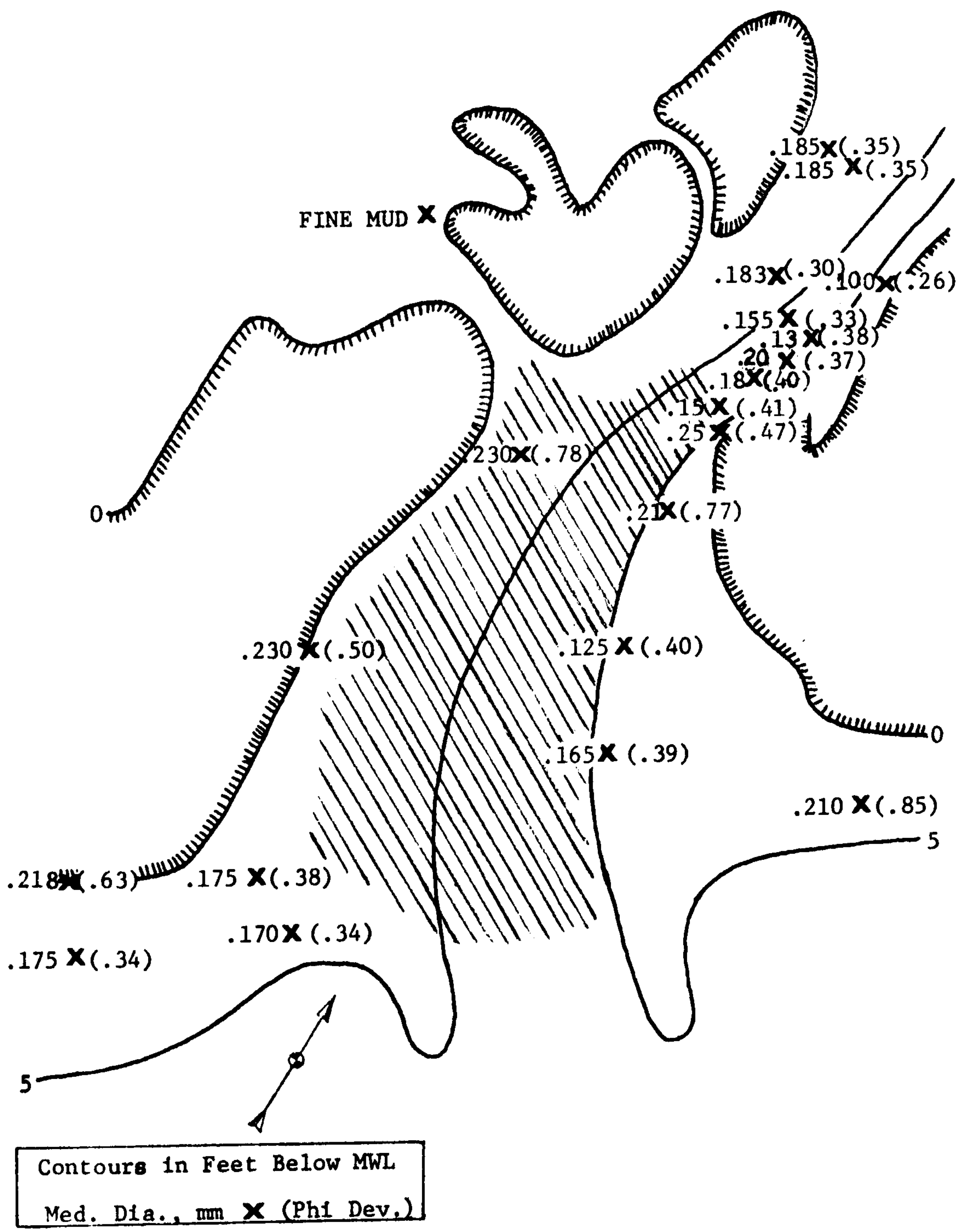



FIGURE 45.--INLET MEDIAN SIZE AND PHI DEVIATION DISTRIBUTION

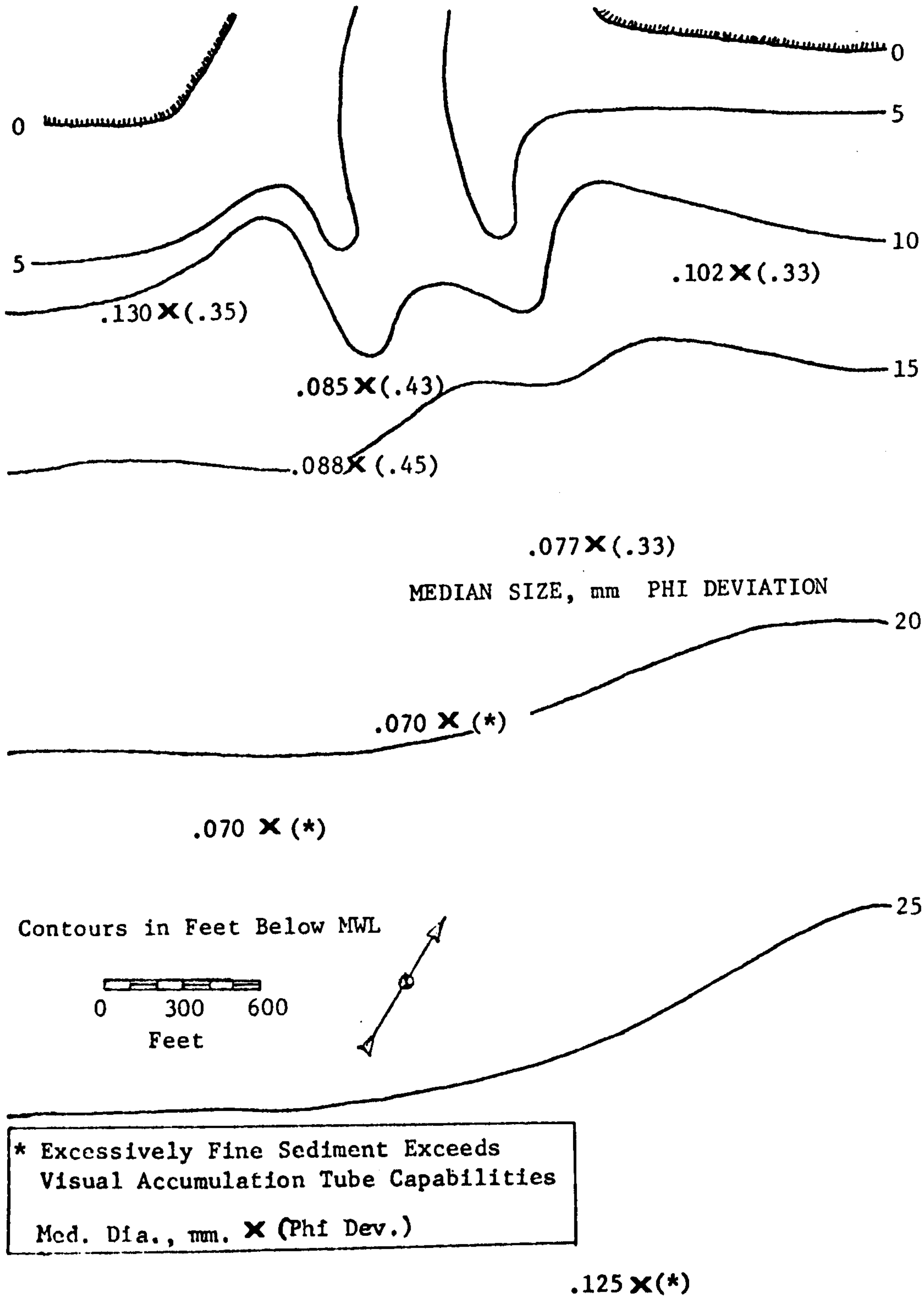



FIGURE 46.--OFFSHORE MEDIAN SIZE AND PHI DEVIATION DISTRIBUTION

in the interior mud flats, at the end of the small dock, and in the deeper gulf waters. Such sizes are indicative of extremely weak current regimes. Observations of the current patterns at the dock during a period of maximum flood revealed that a very slow seaward moving eddy existed there while currents moving bayward in the main channel exceeded two feet per second. Known areas of armoring of the channel floor by large shells are indicated by the cross-hatched portions, since such shells are not reflected by median size distribution.

The remaining samples possessed median diameters close to 0.18 millimeters. This is rather surprising, for Inman reports that this size is most easily transported (24). One would expect to find considerable areas of more stable sediments if the 0.18 millimeter sand were readily eroded. However, it appears that the majority of the inlet is composed of material which is easily eroded. Therefore, the channel bottom must be in a rather constant state of motion due to the influence of prevailing tidal currents. This concept of movable bed is in agreement with evidence presented by Bruun and Gerritsen of a "rolling carpet" being necessary for inlet stability (8).

The phi deviation distribution indicates that those samples with median grain sizes of about 0.18 millimeters are also the best sorted, in accordance with Inman (24).

Analysis of sedimentary characteristics has revealed that major portions of Brown Cedar Cut consist of easily eroded material, intimating that problems of stability related to a decrease in the cross-sectional area are probably minor compared to those of inlet migration and closure due to enroachment of the offshore bar.

## LITTORAL DRIFT ESTIMATIONS

Determination of the amount of sand transported to an inlet mouth is of great importance in evaluating the inlet's stability. Carothers and Innis estimated the gross littoral drift rate at Freeport to be 703,000 cubic yards per year based on the amount of maintenance dredging performed in the Freeport ship channel (10). However, controlled investigations of actual transport rates have yet to be conducted on the Texas coast. Therefore, three methods for estimating the littoral drift rate were employed, with the hope of obtaining values of approximately the same magnitude.

An approximation of the amount of sand introduced to the inlet regime by wave action can be gained by attempting to relate the observed spit growth to local littoral drift conditions. It was previously determined that between October 24, 1970, and February 20, 1971, a total of 36,150 cubic yards of sand accumulated shoreward of the February 20 mean water level contours. Assuming that this represents the total quantity of littoral drift for that period, a gross transport rate of 108,000 cubic yards per year is established. In a similar manner, a net transport rate of 21,570 cubic yards per year towards the west is computed, for a net to gross ratio of 0.2. However, it is highly unlikely that a significant percentage of the total transport load was consumed by spit growth, since most material is either bypassed across the bar or mouth or is deposited at the channel ends. Bruun and Gerritsen found that only between one-fifth and one-tenth of the gross annual transport load was deposited on shoals adjacent to selected inlets (7). Therefore, the above estimates might be low by a factor of from five to ten.

A method for obtaining a rough estimate of the magnitude of littoral drift rates was developed by the U.S. Army Corps of Engineers, and requires a knowledge of shallow water wave characteristics (53). Using hindcast wave data for a location at Caplen, Texas (4), about eighty miles northeast of the inlet, a net westward transport rate of about 19,000 cubic yards per year was calculated, with a gross rate of about 300,000 cubic yards per year. However, local variability, shallow water effects, and hurricane activity will effect the accuracy of applying only three years of theoretical wave data from a distant location to transport rate computations at Brown Cedar Cut. It is considered that larger transport rates than those calculated should be expected.

The final method for drift estimations at Brown Cedar Cut involves a study of observed erosion of adjacent beaches. Two facts are important: the predominate wave direction is from the southeast, and large-scale erosion has been occurring west of the Brazos River mouth since its relocation in 1929 (see Figure 1). If it is assumed that the Brazos River delta blocks all longshore transport of sand from the east, and that continued growth of the delta consumes all sand-size particles transported by the river, then the westward transport rate just west of the mouth is zero. Examination of U.S. Coast and Geodetic Survey Charts from 1858 through 1969 reveals that at a point 9.67 miles west of Brown Cedar Cut beach erosion since 1930 has been negligible. However, the magnitude of shoreline recession occurring since 1930 increases towards the east, becoming a maximum at Brown Cedar Cut. The value of the equilibrium net transport rate is calculated by determining the total volume of material eroded between the point of no erosion and the point of zero transport, and dividing this by the number of years over which the erosion occurred. The net transport rate past the inlet is also of importance, and can be estimated in the same manner.

The total volume of material eroded between 1930 and 1969 was found to be $1.68 \times 10^7$ cubic yards. Dividing this by thirty-nine yields an average net westward littoral drift rate of 431,000 cubic yards per year. Erosion between Brown Cedar Cut and the Brazos River over the same period amounted to $1.26 \times 10^7$ cubic yards, giving a net westward transport rate past the inlet of 323,000 cubic yards per year. Comparing these values to those found by the previous methods indicates that drift rates based on shoreline erosion are considerably higher. However, it is likely that much of the eroded material was not transported by littoral currents, and losses due to other forces must be considered. In the case of Texas beaches, the effect of hurricanes on beach stability is of prime importance. Analysis of beach profiles published by the U.S. Army Corps of Engineers (55) revealed that although Hurricane Beulah crossed the Texas coast at Brownsville, the associated wave and tidal action eroded an average of three hundred sixty-three cubic feet of sand per foot of beach front from the foreshore and berm areas at Sargent. This represents a potential loss of two million cubic yards from the beach areas between the Brazos River and Brown Cedar Cut. Since 1930, most of the twelve hurricanes which affected this area passed much closer to Sargent than did Beulah. Assuming that about one and one-half times as much sand was eroded during each of these storms, a total of about thirty-six million cubic yards of sand may have been removed. However, it should be noted that much of the sand eroded by storms is subsequently returned to the beaches by constructive wave action, so it is difficult to establish a reliable estimate concerning the net effect of hurricanes on littoral drift rates. Assuming that one-fourth of the material eroded during hurricanes was permanently moved beyond the influence of restorative forces, a revised net transport rate of about 92,000 cubic yards per year past the inlet is established.

Considering the many complicating factors affecting littoral drift estimates, only rough approximations of the transport rate past Brown Cedar Cut may be made. It appears that the net transport rate is between 19,000 and 90,000 cubic yards per year, with a value of 50,000 selected as representative. Gross transport rate estimates between 300,000 and 1,000,000 cubic yards per year, and a representative value of about 600,000 is assumed.

## OBSERVED INLET STABILITY

Since its formation, Brown Cedar Cut has exhibited a marked tendency for both geometric and geographic instability. A typical sequence of events characterizes the inlet's response to natural forces on the Gulf coast: The action of large waves and high tides associated with hurricanes, or large amounts of rainfall and run-off, establish a wide, relatively deep channel. This channel has consistently occupied a position very close to the location exhibited on October 24, 1970, as shown in Figure 70. Following this enlargement, the erosive forces of strong currents and high waves are diminished. The inlet mouth migrates westward in response to dominant depositional processes, which produces growth of a large spit on the east side. The rate of inlet migration depends upon the magnitude and duration of the waves from the east and southeast which produce the littoral drift. As the channel lengthens, tidal velocities decrease, and siltation occurs throughout the channel. If undisturbed, migration may continue until the inlet becomes greatly extended, as indicated in Figure 18. At such time, the interchange of gulf and bay waters is effectively nonexistent. However, such extension does not appear to be common. Generally the channel is re-enlarged by waves or currents, the east spit is greatly eroded, and the sequence is repeated. Actual closing of the inlet occurred only between 1964 and 1967, as illustrated in

Figure 20. Apparently wide scale enlargement and shoaling of the inlet by Hurricane Carla initiated irreversible closure tendencies.

Contrary to the pattern of migration described above, during most of the period between September 1967, and November 1970, the inlet remained in the same position. Examination of climatological data for Matagorda (56) revealed that annual precipitation during this interval was from two to twelve inches above normal, with the following local extremes: September 1967, (Hurricane Beulah), 15.5 inches; June 1968, 15.8 inches; and September 1970, 12.4 inches. Runoff resulting from such concentrated periods of rainfall would greatly enhance the flushing capability of currents in the inlet, with subsequent contributions of material to littoral transport or deposition in offshore waters.

Between October, 1970, and February, 1971, a rapid decrease in the cross-sectional area at the mouth resulted from slight westward migration of the channel and growth of a west spit. However, with the subsequent occurrence of a number of winter cold fronts, which forced water out of the bay, the channel maintained relatively constant position and cross-section until April. Substantial ebb currents associated with wind activity from the north apparently precluded ingestion of littoral drift at the gulf entrance, and also actively eroded the inlet banks. Price attributes the north-south orientation and equilibrium position of many larger Texas inlets to the flushing action produced by the passage of such "northers" (44). Although evidence obtained in this study tends to confirm this theory for conditions at Brown Cedar Cut, migration of the channel during the reporting period was probably greater than normal, due to the lack of precipitation and runoff into the bay. Climatological data for Matagorda indicates that precipitation from November to April averaged about two inches below normal. A total of 6.2 inches fell during that time, compared to 5.2 inches in October, 1970 (56).

In addition to ebb currents, wave activity during the winter months appears to enhance the stability. Winter waves are usually larger than average, but highly variable in direction. This directional variability inhibits growth of any one side of the inlet and actively attacks the exposed portions of the spits. In contrast, wave action during the summer apparently causes westward migration of the channel, since the waves are generally lower, more constructive, and arrive primarily from the southeast.

The importance of a bar adjacent to the inlet mouth to the problem of inlet stability has been considered by Carothers (10). This bar may allow significant by-passing of littoral drift along its perimeter, but also tends to decrease the flow velocities developed in the channel. Direct measurement of the extent of the offshore bar at Brown Cedar Cut could be obtained only one day, and the rather limited bar area is shown in Figure 71. Therefore, the degree to which this bar effects the stability of the inlet is unknown. However, from the analysis of coastal charts described under Littoral Drift Estimations, it appears that the inlet did not significantly interfere with transport of sand to western beaches. The erosion rate of these beaches was the same as that for the eastern or updrift side of the inlet. Therefore, it is assumed that significant quantities of material are by-passed across the inlet, and that the bar probably plays an important role in this process.

Perhaps the most important, but most subtle of the processes leading to stability has been the erosion of the gulf beaches adjacent to the inlet. Prior to 1930, the east end of Matagorda Peninsula maintained a relatively stable, unbroken profile to the west. Although hurricanes caused numerous local breakthroughs, such channels apparently were rapidly filled by sand transported along the shore by wave action. However, between 1930 and 1969, erosion of over six hundred and fifty yards of beach front has reduced the effect of frictional resistance on tidal currents flowing through Brown Cedar Cut, thus allowing velocities to remain relatively high. Therefore, maintenance of a reasonably stable channel has been enhanced.

# THEORETICAL INLET STABILITY

In considering the prediction of the stability of tidal inlets on sandy coasts various investigators have proposed a number of relationships between measurable environmental parameters and observed inlet stability. Since the stability of Brown Cedar Cut has been previously established, it is of interest to determine how well theoretical predictions of this inlet's stability compare to the observed. It should be noted, however, that short-term processes such as surface run-off and hurricane activity are of considerable importance to the stability of this inlet, and are not considered in the stability relationships discussed below.

## Channel Cross-Section vs. Tidal Prism

One of the first methods for relating inlet properties to the predicted inlet stability was proposed by O'Brien in 1931 (38). It was found that an approximately linear relationship between the minimum flow cross-sectional area of the entrance channel, A, and the diurnal range tidal prism, $\Omega$, was exhibited by a large number of inlets on the Pacific Coast. In a later paper, which included data from additional inlets throughout the United States, O'Brien reported the following linear relationship for all non-jettied stable inlets:

$$A = 2 \times 10^{-5} \, \Omega$$

where A is in square feet and $\Omega$ is in cubic feet (39). Based on this equation, and employing an observed minimum cross-section of about 2000 square feet, a tidal prism of $1 \times 10^8$ cubic feet is predicted for stability of Brown Cedar Cut. Comparing this to the observed adjusted tidal prism of $2.8 \times 10^8$ cubic feet reveals that according to O'Brien's criterion, the inlet is unstable with a tendency for erosion. This type of instability is not characteristic of the conditions at Brown Cedar Cut, which exhibit a pattern of closure due to insufficient tidal action. The wide discrepancy between O'Brien's stability criterion and the observed conditions may result from the presence of the extensive bay island network adjacent to the inlet. Much of the tidal energy is consumed by friction along the shallow bottom, rather than in channel maintenance. If a single deep channel existed the area to tidal prism ratio would probably more closely approximate O'Brien's value.

## Littoral Drift vs. Discharge Quantities

A second method will be considered which utilizes the relationship between littoral drift and tidal current activity. In an investigation of various natural tidal inlets located on sandy coasts, Bruun and Gerritsen determined the ratios of the tidal prism, $\Omega$, in cubic yards, and maximum discharge at spring tide conditions, $Q_m$ in cubic yards, to the annual gross littoral drift rate, M, in cubic yards per year (8). It was found that those inlets having a value of $\Omega/2M$ greater than three hundred possessed a high degree of stability. Those with values of $\Omega/2M$ less than one hundred tended to be unstable, and were characterized by the presence of shallow bars and shoals adjacent to the inlet mouth, with one or more shifting interior channels. For an adjusted tidal prism of $2.80 \times 10^8$ cubic yards and a gross annual drift rate of 600,000 cubic yards per year, a value of $\Omega/2M$ of 24.3 was computed for Brown Cedar Cut. This value falls well within the reported range of values for unstable inlets, and correctly predicts the observed predominance of littoral drift over tidal flow. Historical fluctuations in channel geometry and position also correspond to the descriptions of unstable channels given by Bruun and Gerritsen.

Concerning values of $Q_m/M$, it was concluded that values greater than .01 generally indicate more stable conditions than values less than .01. For a $Q_m$ of two hundred twenty-two cubic yards per second a value of $Q_m/M$ of .00037 is obtained for Brown Cedar Cut, and highly unstable conditions with a marked tendency for deposition are again indicated. Thus, prediction of stability based on littoral drift vs. discharge quantities appears to yield accurate repsentations of the stability characteristics exhibited by Brown Cedar Cut.

## Stability Shear Stress

A criteria for inlet stability has been suggested by Bruun and Gerritsen whereby it is assumed that a certain value of the average shear stress throughout the channel corresponds to stable conditions (8). In this context, stable conditions do not require that the bottom material remain stationary, but that the net transport of sediment within any section is zero. This stability shear stress, $\tau_s$, is given by:

$$\tau_s = 28.5\ n^2 R^{1/3} V_m$$

where n is Manning's coefficient, R is the hydraulic radius, and $V_m$ is the maximum flow velocity during spring tide conditions. Substituting the appropriate values for n and R, and selecting a representative value of $V_m$ = 1.7 feet per second from observed velocity variations, a stability shear stress of .055 pounds per square foot is obtained for flow conditions at Brown Cedar Cut. This agrees exactly with the value of critical shear stress for general movement determined in laboratory experiments discussed previously. However, in considering the effects of medium littoral drift and sediment load on shear stress, Bruun and Gerritsen suggest a value of .092 pounds per square foot (8). Therefore, it would appear that according to the above stability shear stress criterion, tidal velocities developed within Brown Cedar Cut during the three month reporting period are not of sufficient magnitude to maintain a stable channel. Widespread deposition of littoral drift introduced at the inlet mouth is predicted to occur throughout the channel.

## Depositional Patterns

The final method for prediction of inlet stability was proposed some time ago by Lucke (35). Rather than considering hydraulic and geometric parameters, Lucke proposed a theory relating the long-term stability of an inlet to the configuration of associated bay islands and channels. Figure 47 presents an idealized sequence of events in the history of a stationary barrier beach inlet. Based on Lucke's hypothesis, the patterns exhibited by the bay delta adjacent to Brown Cedar Cut indicate an inlet which possesses long-term geographic stability, and suggests that the system is in an early stage of development. Although sufficient physical evidence was available to determine this directly, from an historical viewpoint the ability to predict inlet stability from depositional patterns is of importance. In addition, it is noted that Figure 47 predicts almost complete filling of East Matagorda Bay in the vicinity of Brown Cedar Cut at some future date.

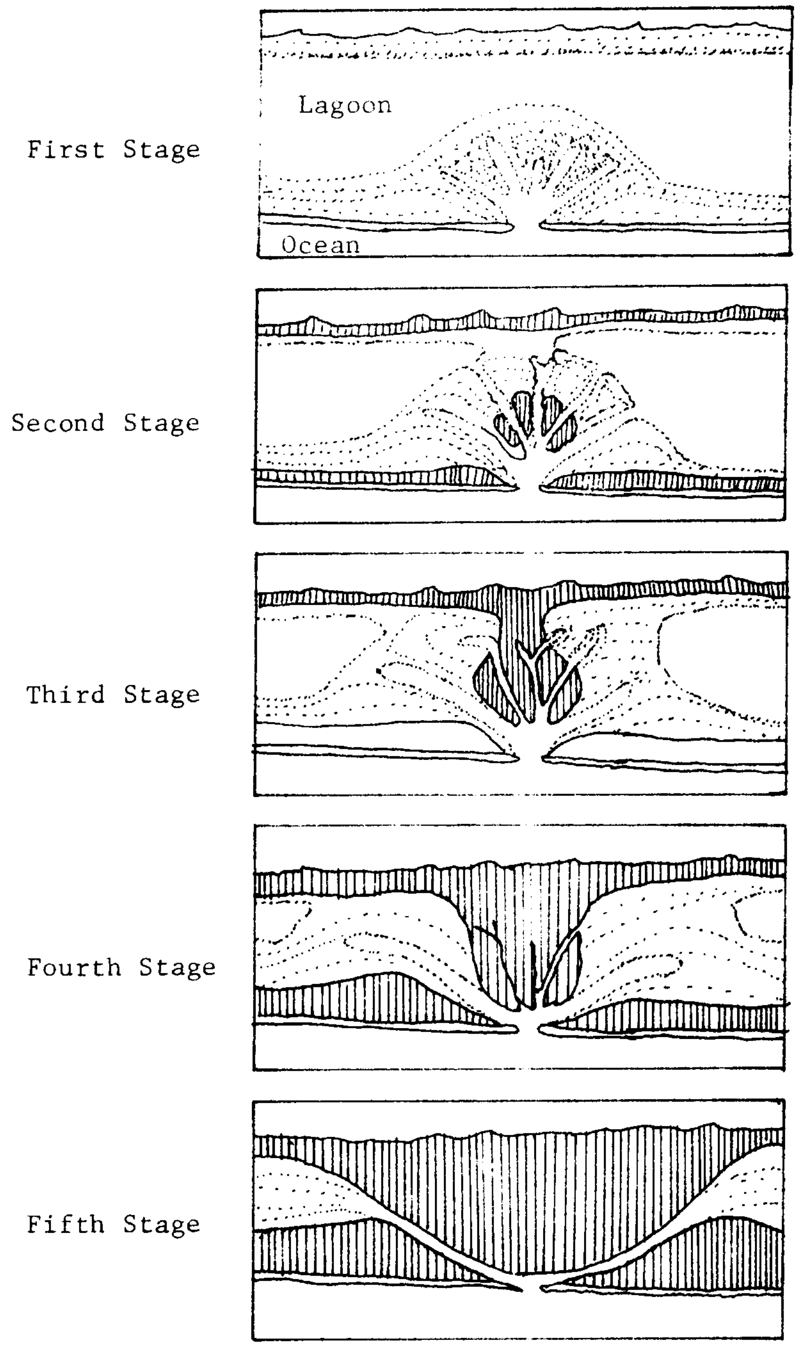



FIGURE 47.--IDEALIZED STAGES OF DEPOSITION IN A TIDAL LAGOON FOR A STATIONARY INLET (AFTER LUCKE(35))

## CONCLUSIONS AND RECOMMENDATIONS

Brown Cedar Cut may be defined as an unstable barrier beach inlet with generally insufficient tidal flow to prevent deposition of sand in the channel, and subsequent migration in the direction of littoral drift. The existence and stability of the inlet are controlled primarily by the action of hurricanes and runoff during periods of extreme precipitation, which scour the channel bottom and adjacent portions of the peninsula. Recession of the gulf shoreline is enhancing the long-term stability of the inlet by significantly reducing the distance between bay and gulf. During the winter, short-term stability is aided by the strong north winds which blow for extended periods and produce conditions of maximum ebb flow. However, in the summer the velocities produced by normal tidal fluctuations are normally insufficient to maintain a stable channel, and migration of the inlet occurs in the direction of predominate littoral drift. Although wave action is found to cause some direct recession of the inlet shorelines, its most important effect is to introduce large quantities of littoral drift to the inlet flow regime and to aid in the creation and enlargement of bars and shoals adjacent to the inlet mouth. Growth of spits on either side of the inlet was found to be greatest when high wave activity was combined with the relatively small tidal ranges associated with semi-diurnal tides. Although modification of typical wave refraction patterns and associated spit configurations is accomplished by tidal currents, the net effect of wave activity is to decrease the stability of Brown Cedar Cut.

Application of selected stability criteria developed by previous investigators to the environmental parameters determined at Brown Cedar Cut indicate that for the most part the theoretical stability of the inlet agrees well with that observed.

Indirect determination of velocities based on tidal prisms was found to be complicated by the effects of water introduced into the bay from the Intracoastal Waterway, as well as by the uncertainty involved in measuring the bay tides at only one location. To determine an accurate representation of the relationship between the inlet flow characteristics and bay tidal variations, a more comprehensive data-gathering program is recommended. Installation of a number of tide gages at strategic locations throughout the bay, combined with direct determinations of velocity through the inlet and locations of significant exchange between the bay and the Intracoastal Waterway should result in an increased understanding of this relationship.

Measurement of current velocities through the inlet revealed a linear dependence of velocity on the square root of the tidal differential between the channel ends. However, agreement with Manning's equation was not achieved due to an unknown flood velocity component. Therefore additional correlation of inlet velocities with observed tidal differentials combined with application of more sophisticated theoretical relationships between tidal parameters and inlet velocities is recommended.

Final consideration should be made of the importance of a stable inlet between East Matagorda Bay and the Gulf of Mexico. Since the early 1900's, when fishermen attempted to artificially create such an inlet, it has been realized that the introduction of gulf waters to the bay was apparently beneficial to commercially valuable organisms, e.g. oysters, shrimp, game fish. Extreme salinities in the bay can be modified by such inflow, and natural flushing of polluted waters is enhanced. In recent years, major development of beach homes has occurred along Caney Creek, and at present many artificial tidal channels are being dredged in the marshlands adjacent to the Intercoastal Waterway near Sargent to provide "on the water" homesites. That such activities are detrimental to the coastal animal population is an understatement. Such domestic activities, as well as continuing industrial pollution of Caney Creek, have probably degraded the water quality of the surrounding wetlands significantly. Alleviation of pollution and salinity problems may be enhanced by a larger and more stable gulf entrance to East Matagorda Bay. From a purely hypothetical viewpoint, such an inlet will be considered below, but it must be emphasized that if the occasion for actual construction ever arises, comprehensive studies must first be performed to determine the detailed characteristics of tidal flow in the bay, as well as the long-term benefits of an inlet to natural inhabitants. The convenience of a gulf entrance to a few local recreational boats is of little importance when compared to possible degradation of biological habitats.

In considering the location for a stable inlet to East Matagorda Bay, the findings of Price (44) are recalled: stable inlets occur at the southwest ends of central Texas bays, where the long fetch allows north winds to produce ebb currents having great scour potential. Remembering also that the shoal bay islands exert considerable friction on tidal currents, and also apparently affect O'Brien's relationship between tidal prism and cross-sectional area (39), location of the inlet adjacent to deeper portions of the bay would probably be desirable. Such conditions are available at a point about seven miles east of the Colorado River, where a minimum width of the peninsula of 1100 yards is exhibited. Using the observed adjusted tidal prism of $2.8 \times 10^8$ cubic feet, a cross-sectional channel area of 5600 square feet is predicted for stability by O'Brien's criterion. In light of the large quantities of littoral drift along the coast, it is quite probable that a jettied entrance and by-passing of littoral materials would be required for stability of such an inlet.

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# APPENDIX--CURRENT MEASUREMENTS

This appendix presents results of a twenty-five hour velocity measurement study performed at Brown Cedar Cut on March 4 and 5, 1971. A Gurley-Price current meter suspended on a rod from a small boat was used to determine velocity vs. depth profiles. These measurements were taken at approximately two hour intervals at the stations indicated in Figure 48. The channel cross-section was obtained using both a graduated rod and an ultrasonic fathometer. The following geometric parameters were established: cross-sectional area, 2480 square feet; wetted parimeter, 560 feet; hydraulic radius, 4.43 feet. The results are presented in two sets of figures.

Figures 49 through 61 illustrate the actual velocity profiles obtained, and are intended for use in determining bottom shear stress as well as for delineating irregularities in flow velocity. Figures 62 through 68 present the cross-channel distribution of velocity, and are intended for use in calculating the quantity of flow through the channel. It should be noted that flood magnitude and duration far exceed those of ebb, a somewhat unusual condition when compared to the average velocity characteristics for the entire reporting period. This occurence of flood predominance resulted from the effects of a strong north wind which had blown for about forty hours on March 3 and 4. Substantial lowering of the bay waters had occurred, but by the time velocity observations commenced, above-average quantities were required to replenish the bay.

A time history of the instantaneous average velocity and discharge is presented in Figure 69. These were obtained from Figures 62 through 68 by application of the continuity equation,

$$Q_t = \sum_{i=1}^{n} A_i V_i \qquad \text{and} \qquad V_t = \frac{Q_t}{\Sigma A_i}$$

where $Q_t$ is the average instantaneous discharge, n is the number of areal segments between isovels, $A_i$ is the area of the ith segment, $V_i$ is the average instantaneous velocity of the ith segment, and $V_t$ is the average instantaneous velocity of flow through the channel.

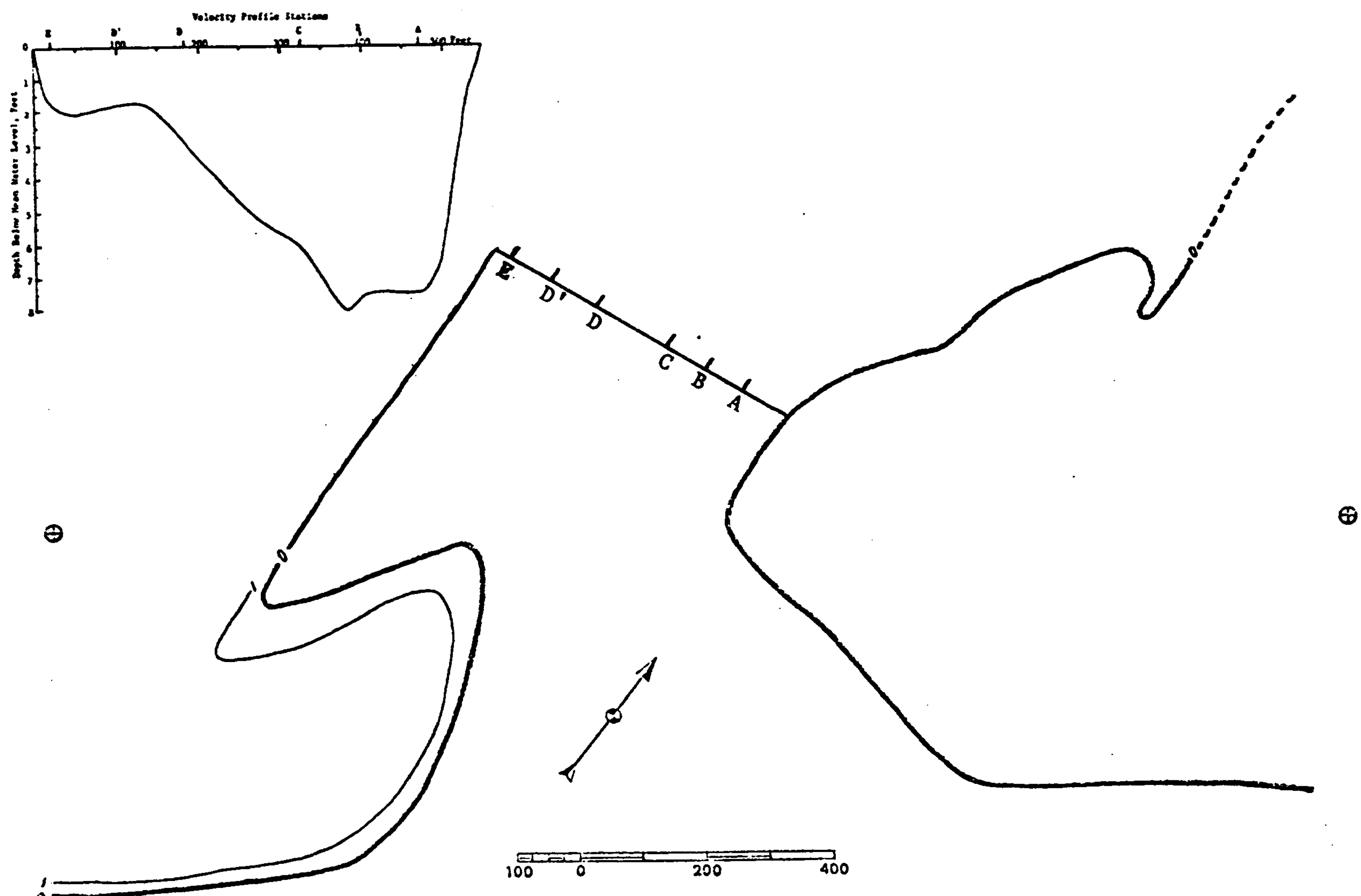



FIGURE 48.--LOCATION OF VELOCITY MEASUREMENT STATIONS

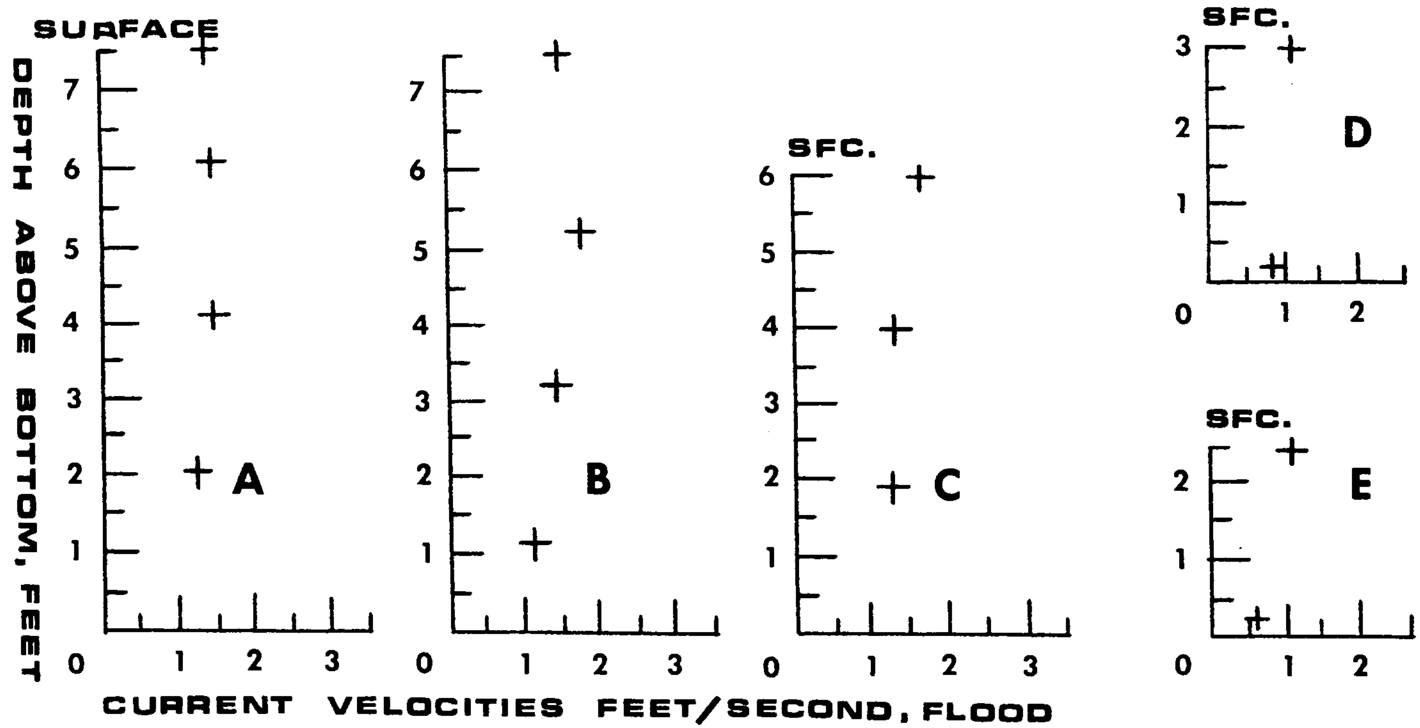



Figure 49.–Vertical Velocity Profiles, 1435 4 March 1971

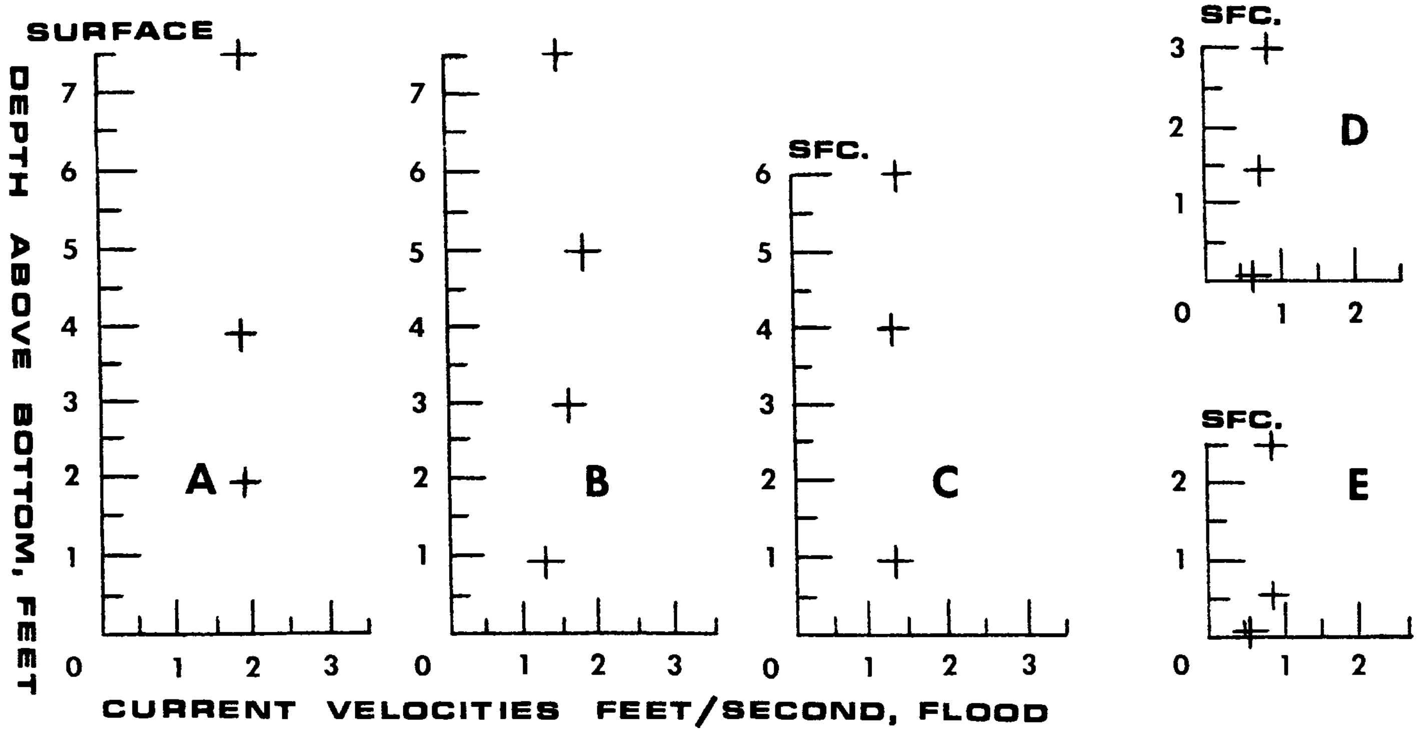



Figure 50.—Vertical Velocity Profiles, 1605 4 March 1971

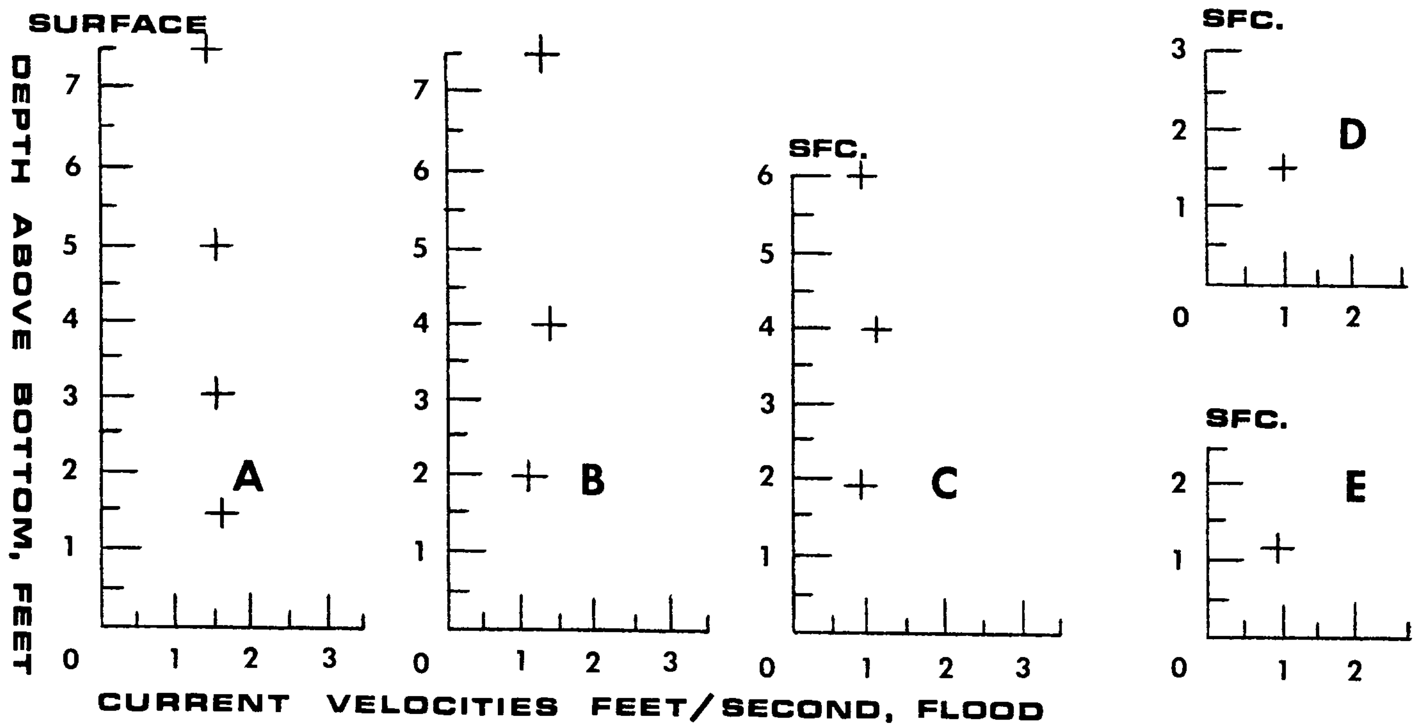



Figure 51.—Vertical Velocity Profiles, 1735 4 March 1971

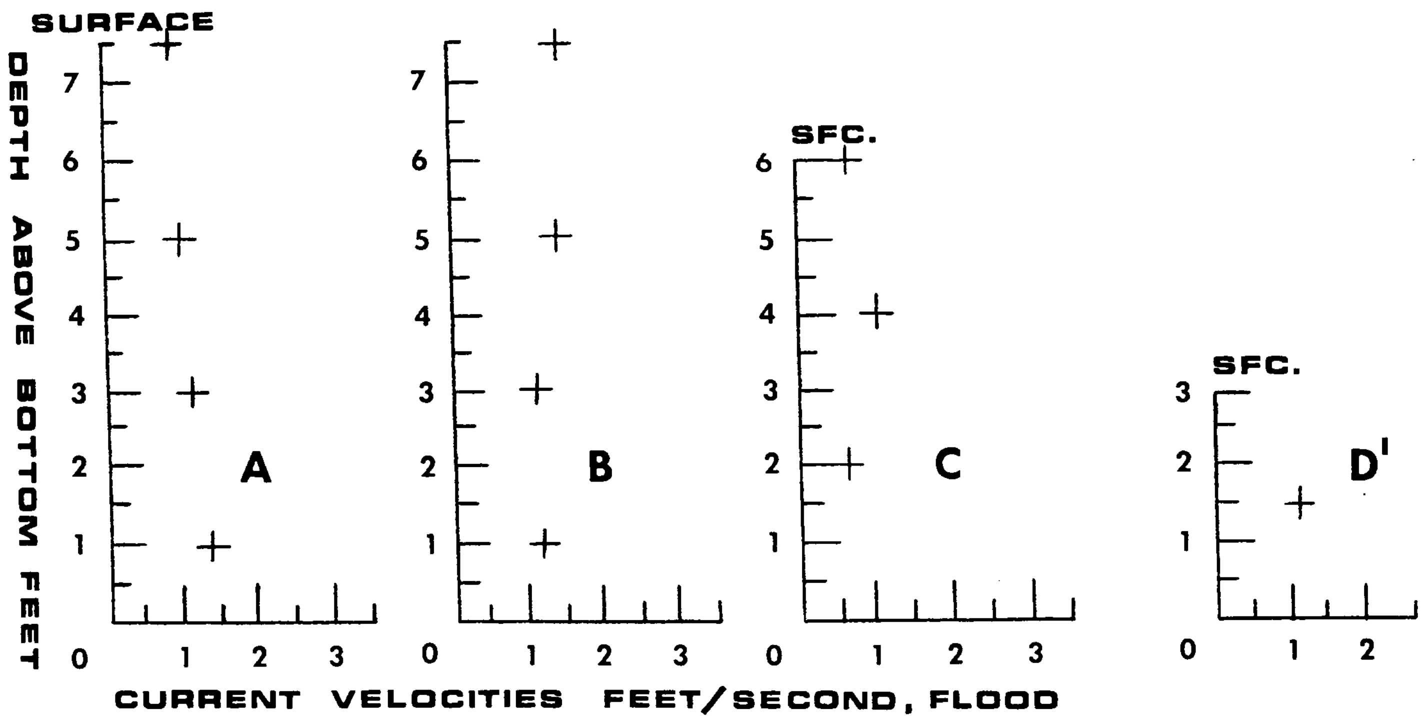



Figure 52.-Vertical Velocity Profiles, 1916 4 March 1971

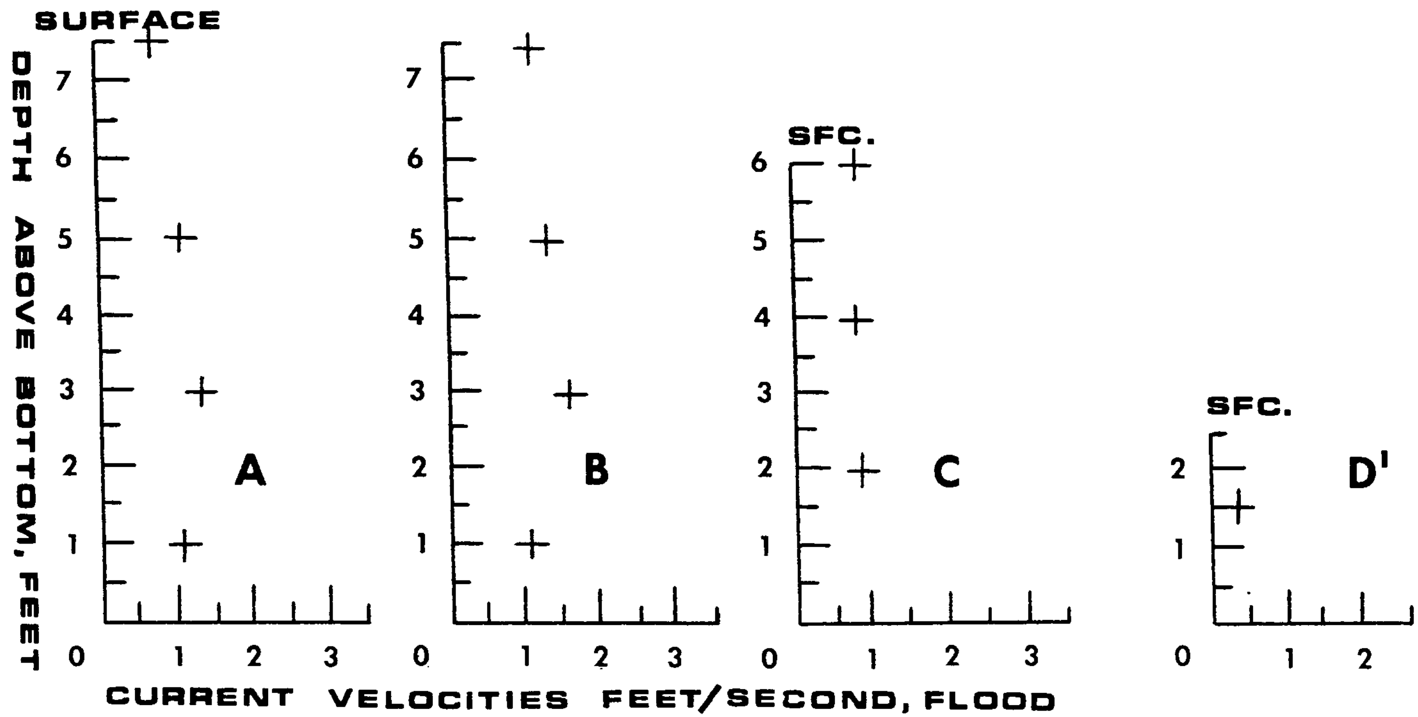



Figure 53.-Vertical Velocity Profiles, 2110 4 March 1971

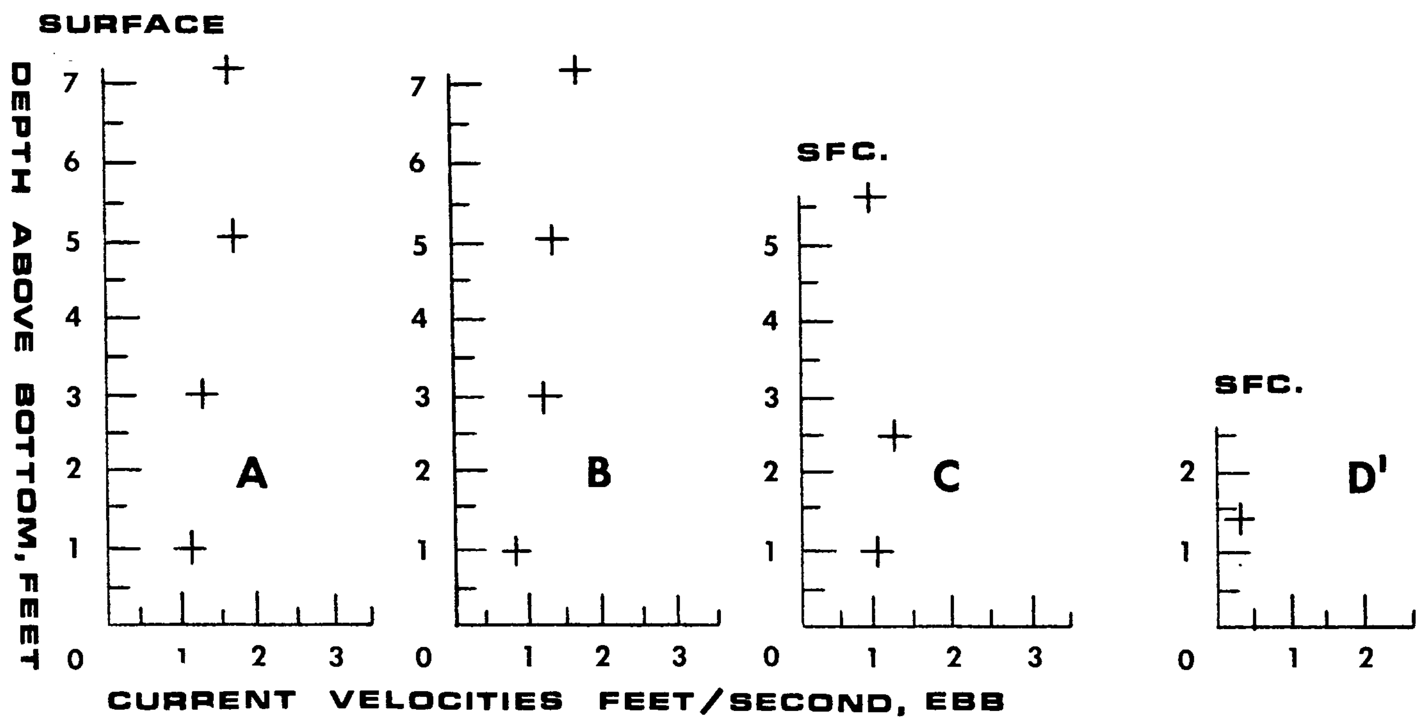



Figure 54.–Vertical Velocity Profiles, 0100 5 March 1971

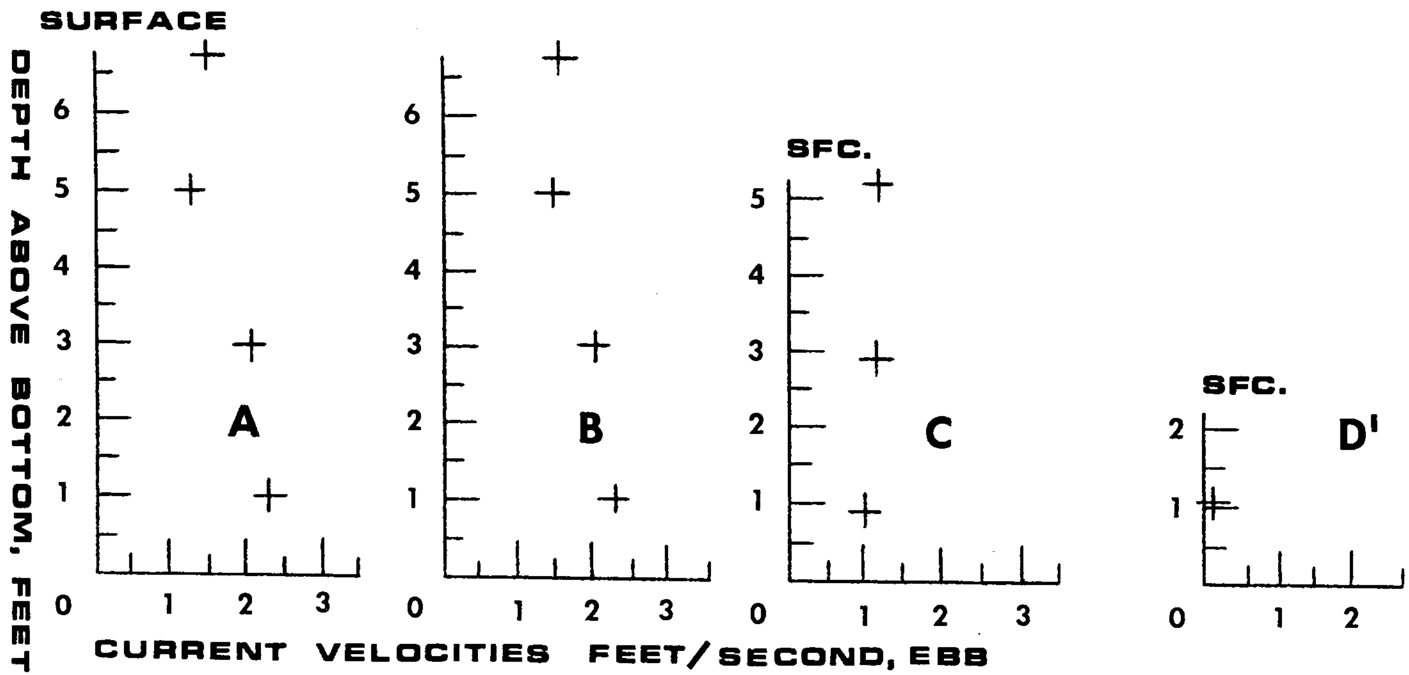



Figure 55.–Vertical Velocity Profiles, 0310 5 March 1971

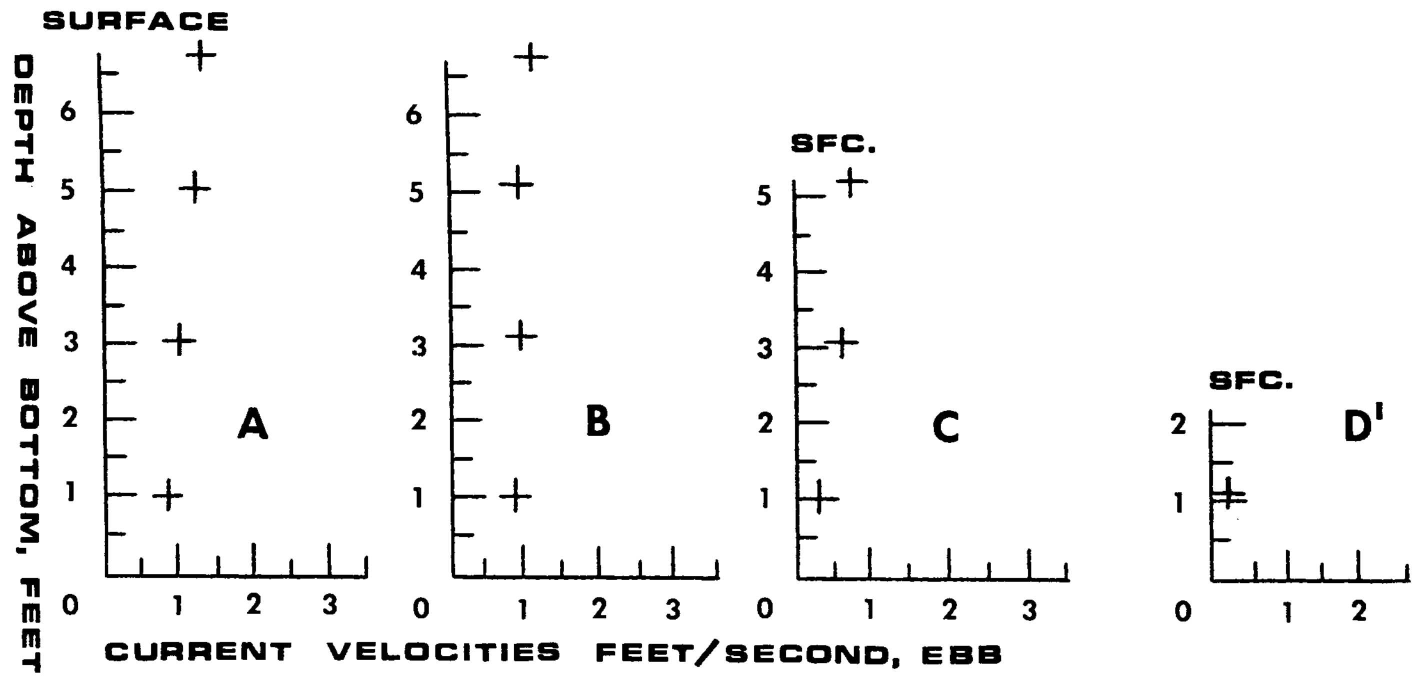



Figure 56.–Vertical Velocity Profiles, 0550 5 March 1971

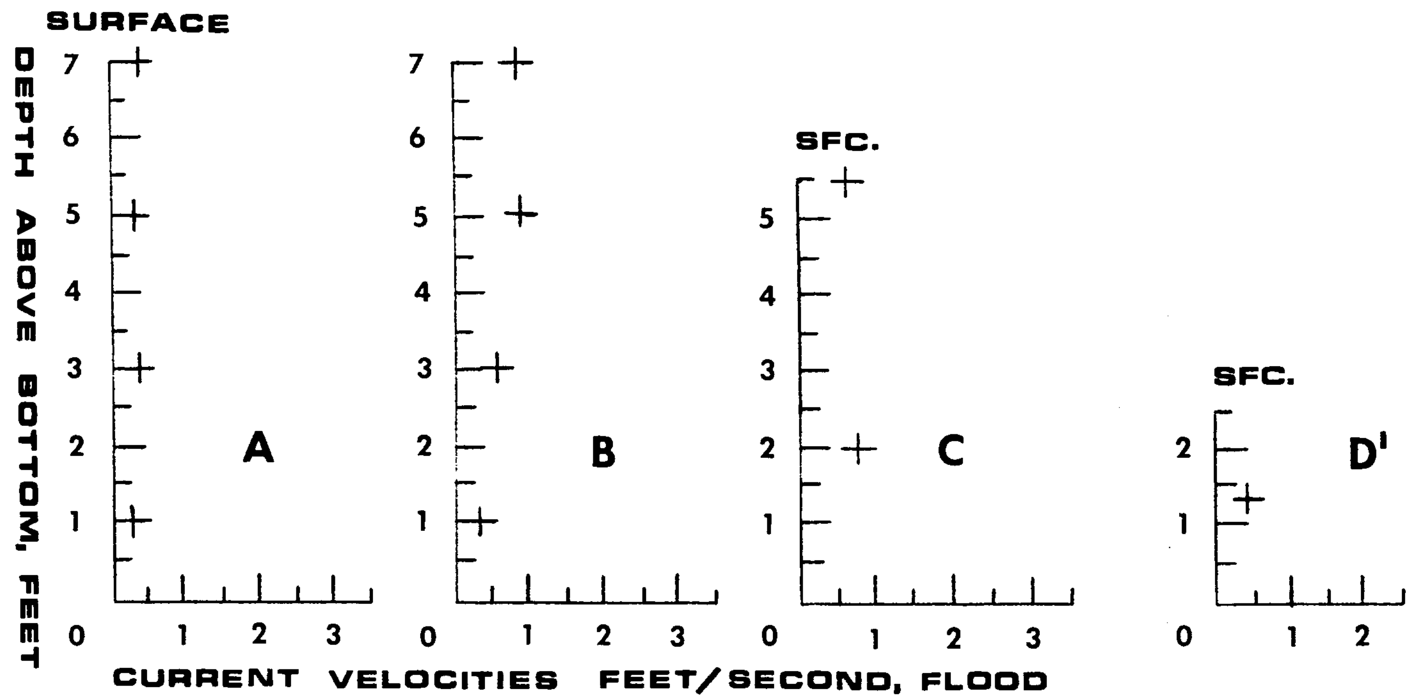



Figure 57.–Vertical Velocity Profiles, 0745 5 March 1971

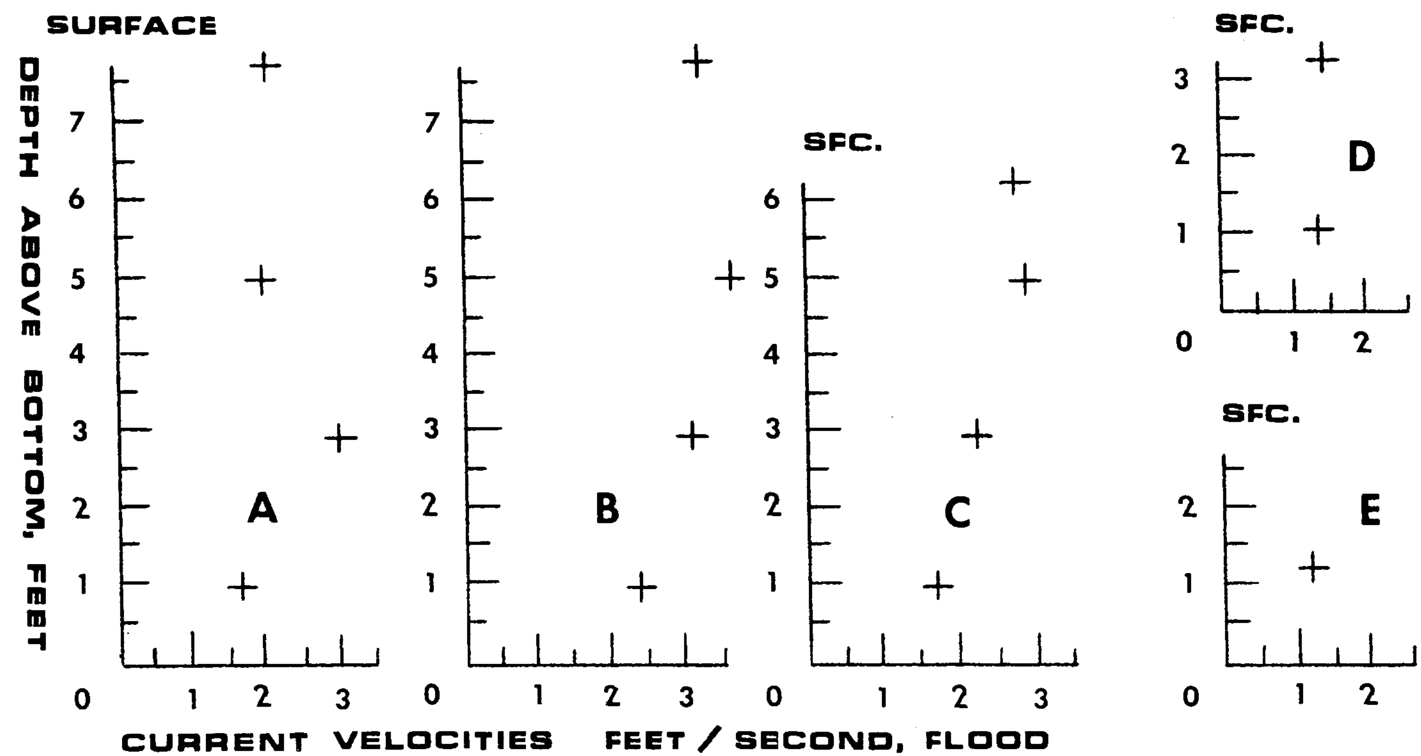



Figure 58.–Vertical Velocity Profiles, 1000 5 March 1971

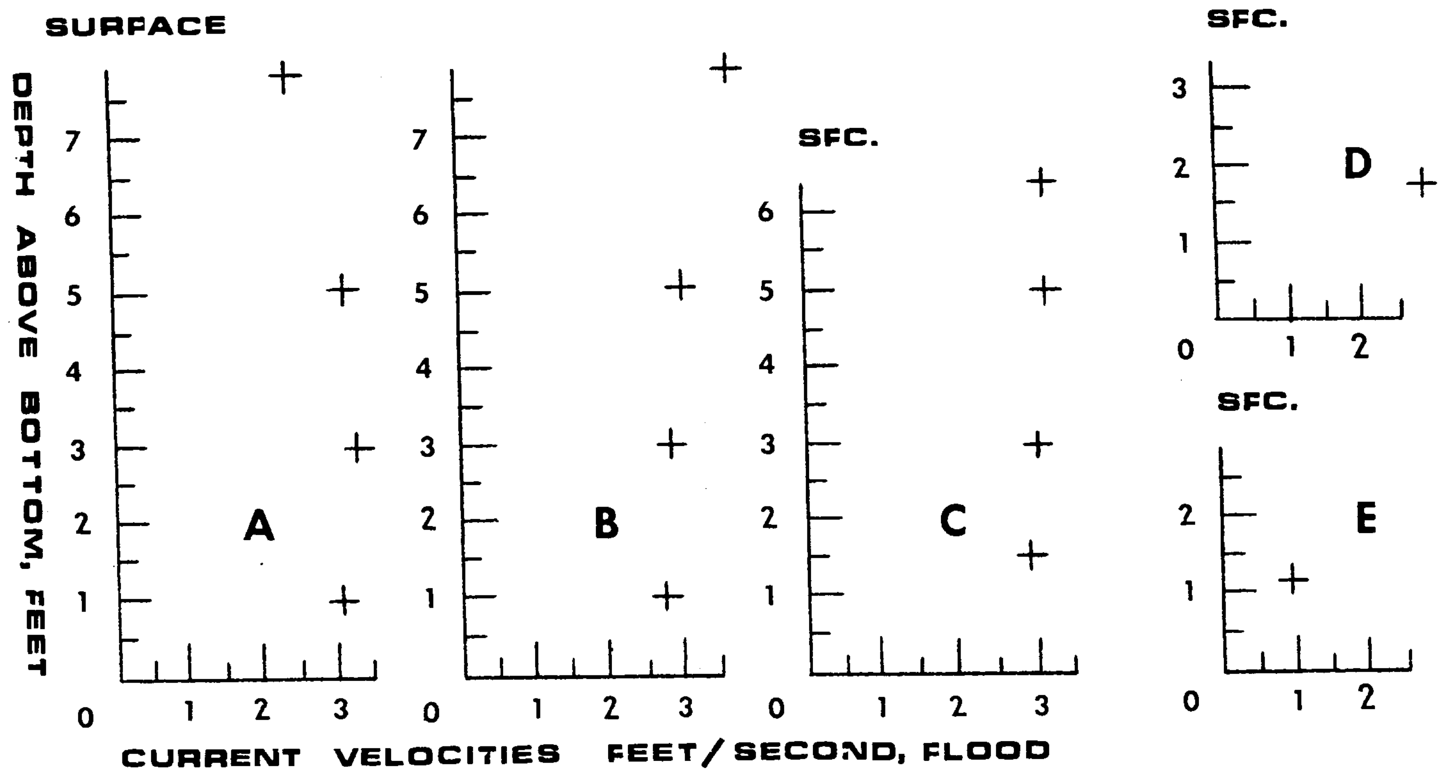



Figure 59.-Vertical Velocity Profiles, 1120 5 March 1971

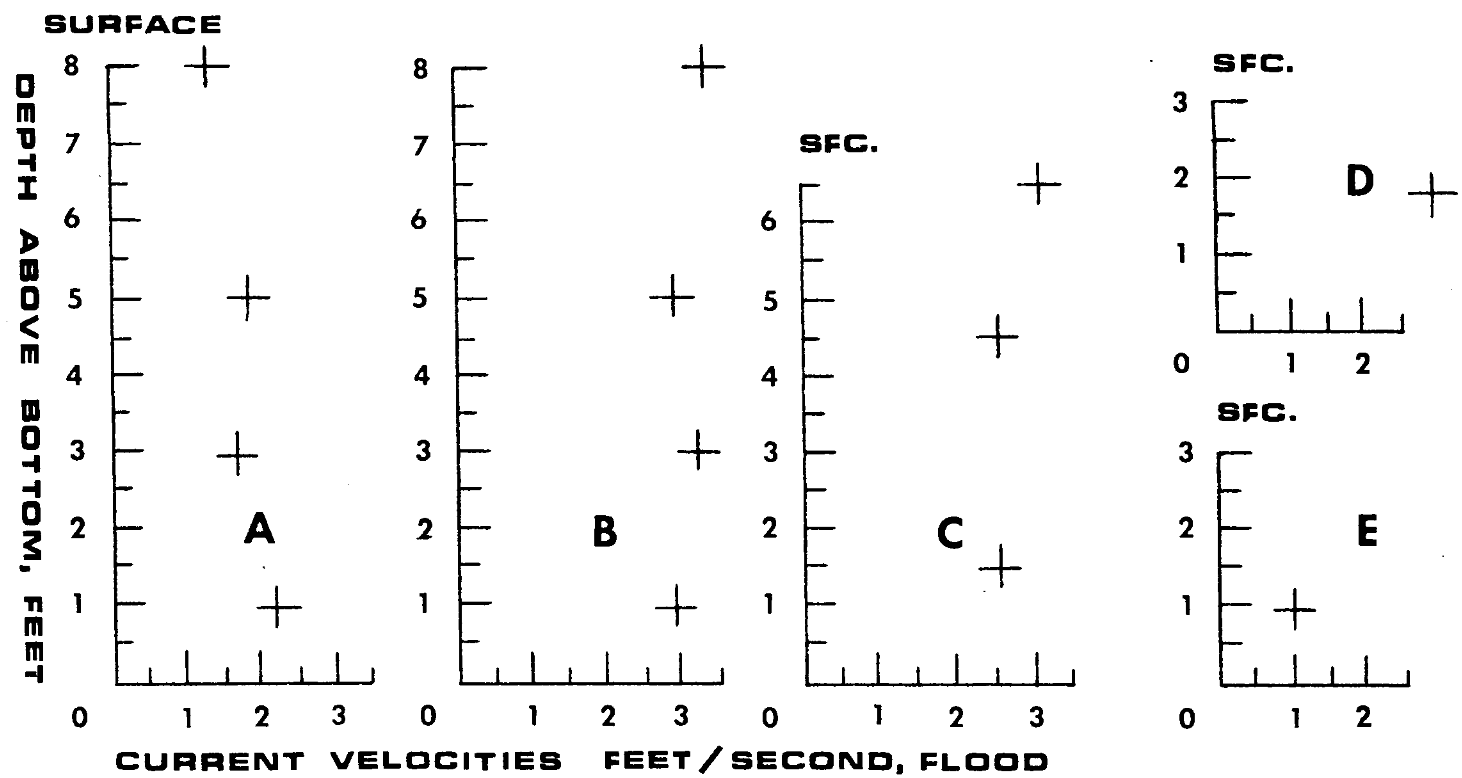



Figure 60–Vertical Velocity Profiles, 1315 5 March 1971

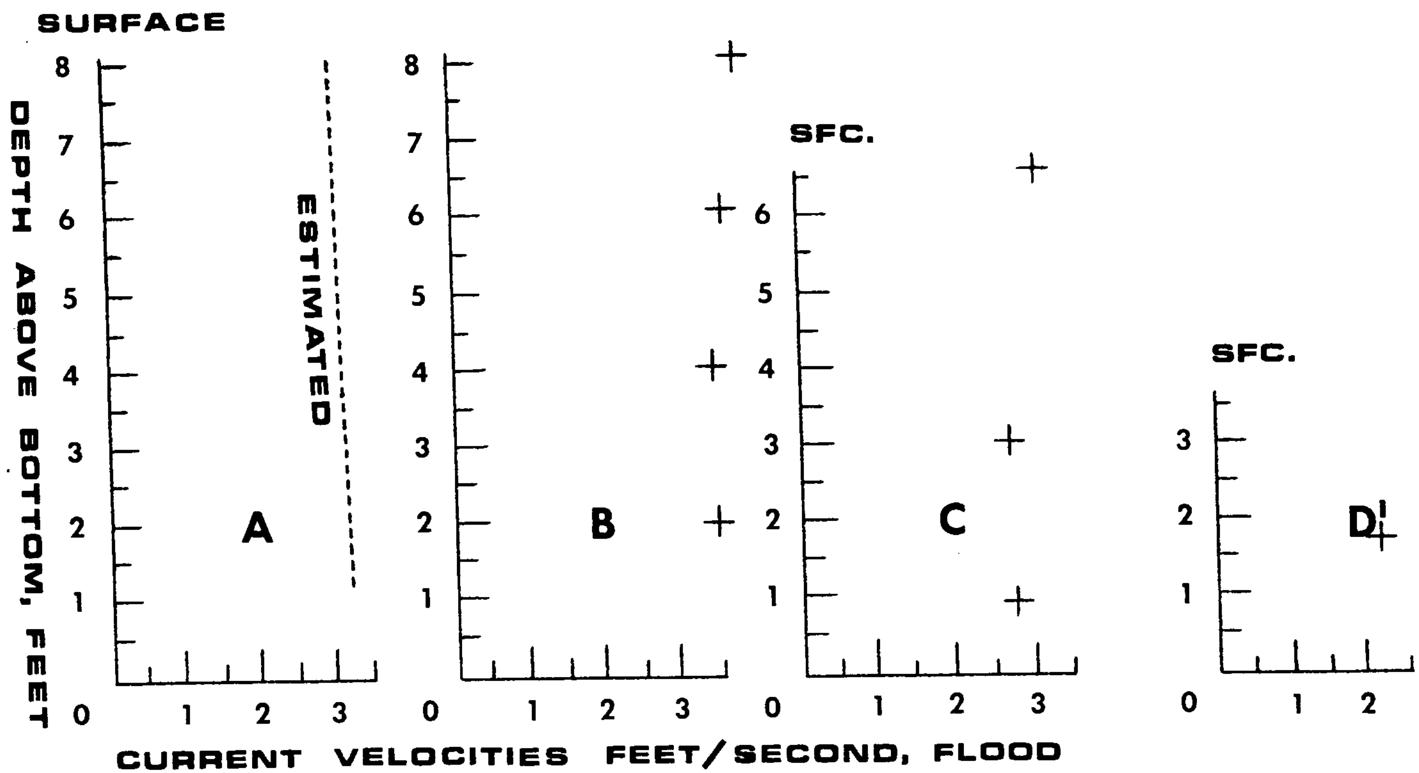
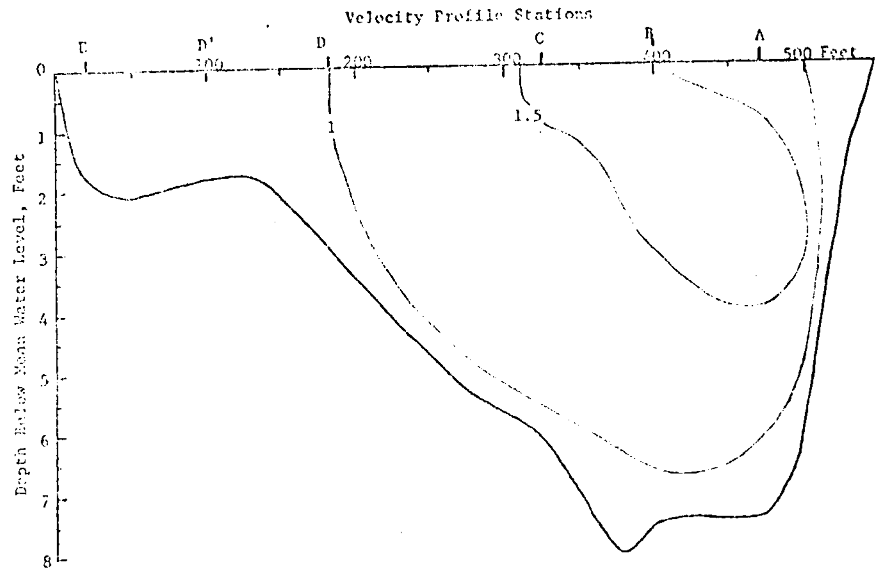



Figure 61.-Vertical Velocity Profiles, 1530 5 March 1971

1435




1605

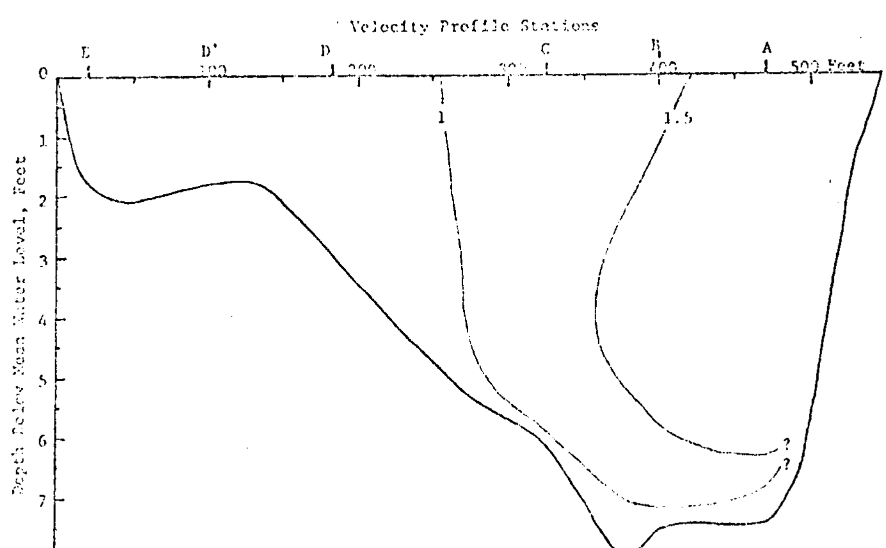
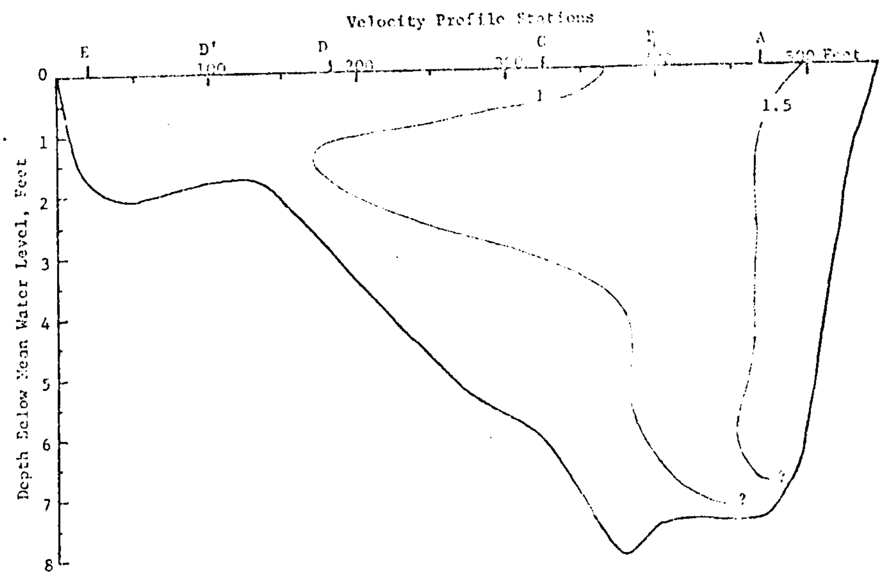



FIGURE 62.--CROSS-CHANNEL FLOOD VELOCITY DISTRIBUTION,
1435 AND 1605 4 MARCH, 1971

1735




1916

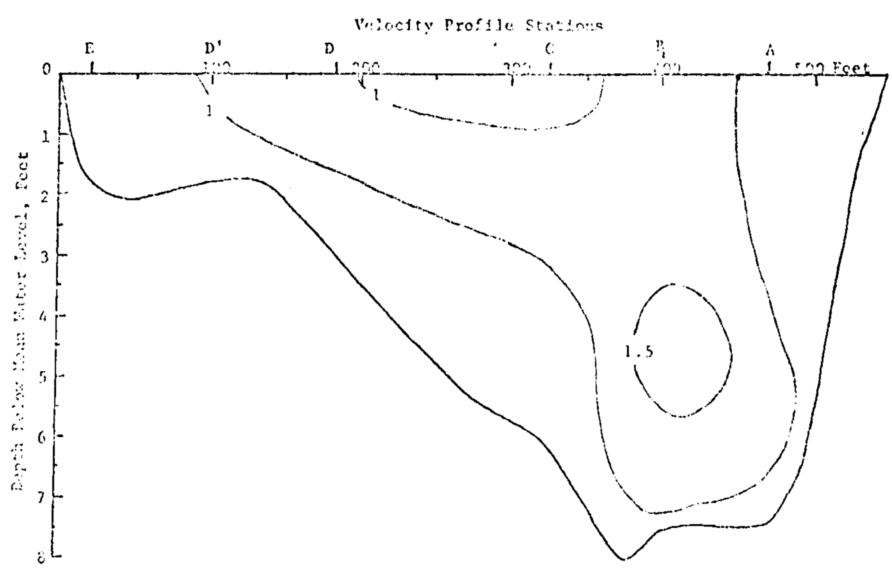



FIGURE 63.--CROSS-CHANNEL FLOOD VELOCITY DISTRIBUTION, 1735 AND 1916 4 MARCH, 1971

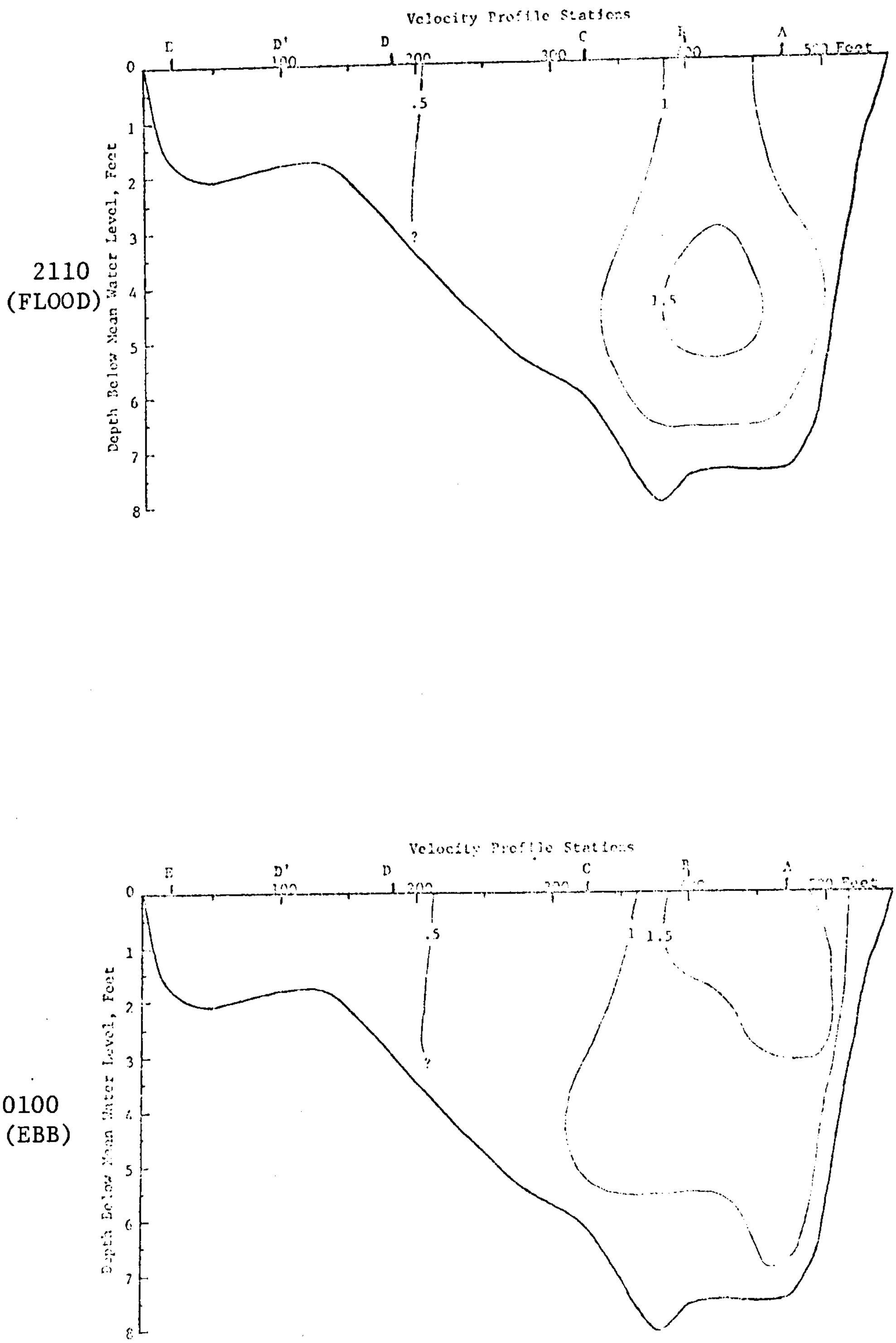
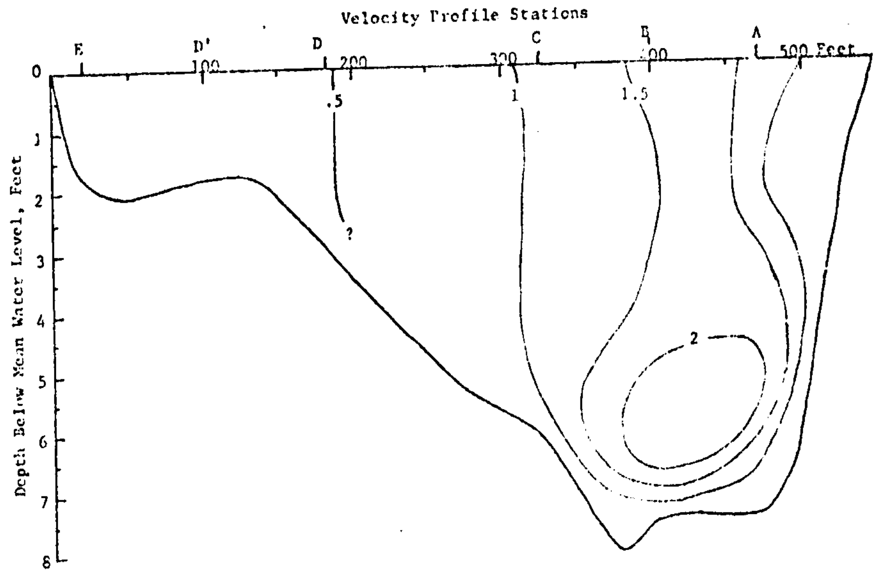



FIGURE 64.--CROSS-CHANNEL VELOCITY DISTRIBUTION,
2110 4 MARCH AND 0100 5 MARCH, 1971

0310




0550

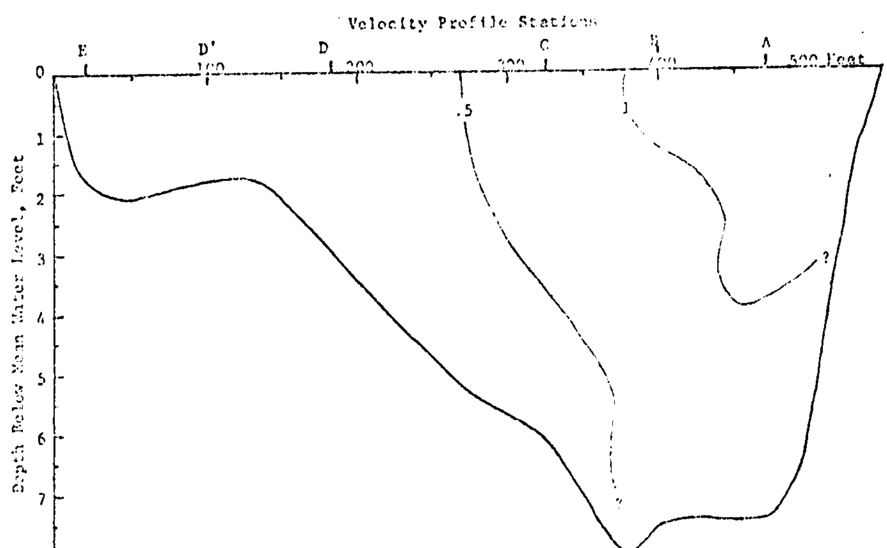
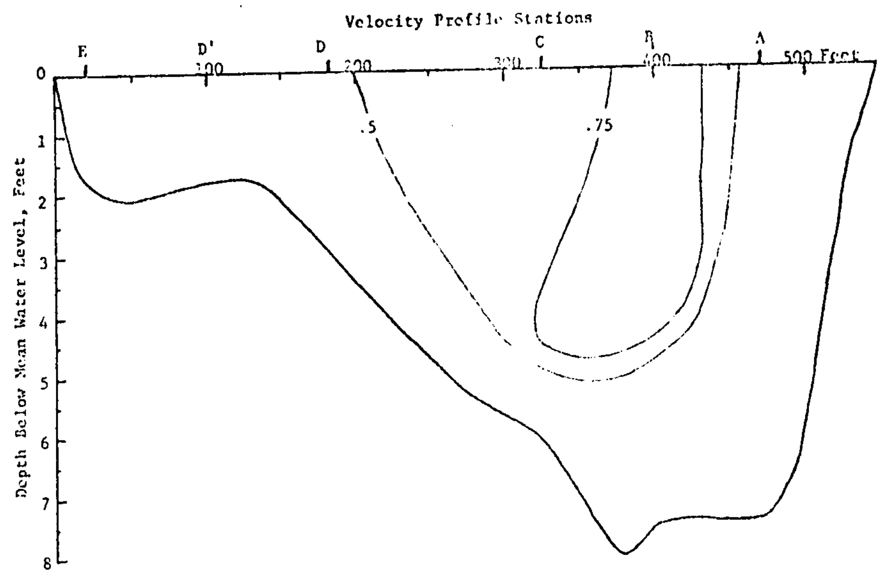



FIGURE 65.--CROSS-CHANNEL EBB VELOCITY DISTRIBUTION, 0310 AND 0550 5 MARCH, 1971

0745




1000

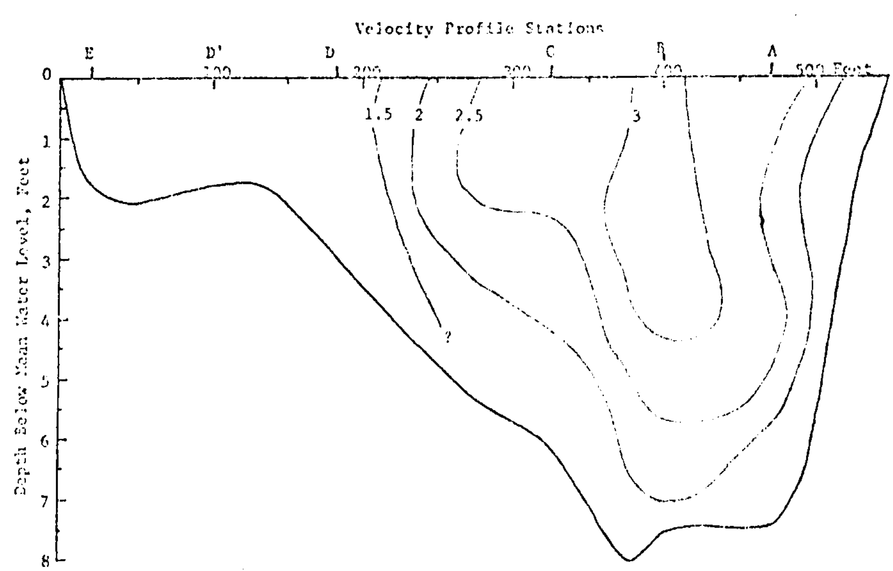
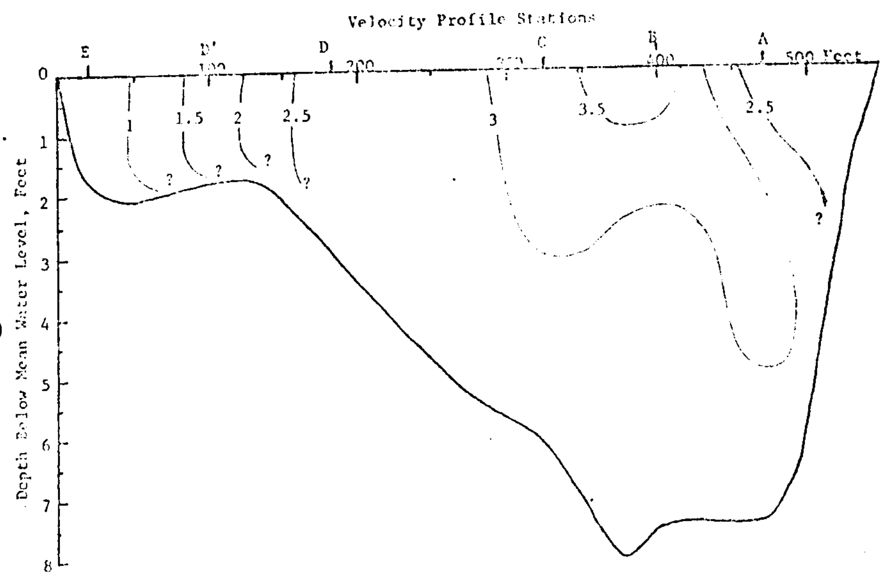



FIGURE 66.--CROSS-CHANNEL FLOOD VELOCITY DISTRIBUTION, 0745 AND 1000 5 MARCH, 1971

1120




1315

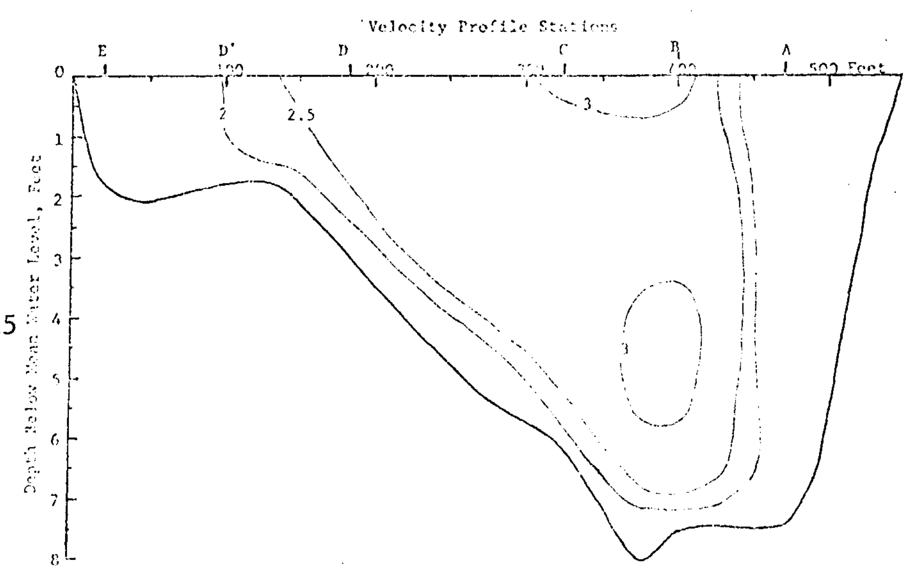



FIGURE 67.--CROSS-CHANNEL FLOOD VELOCITY DISTRIBUTION, 1120 AND 1315 5 MARCH, 1971

1530

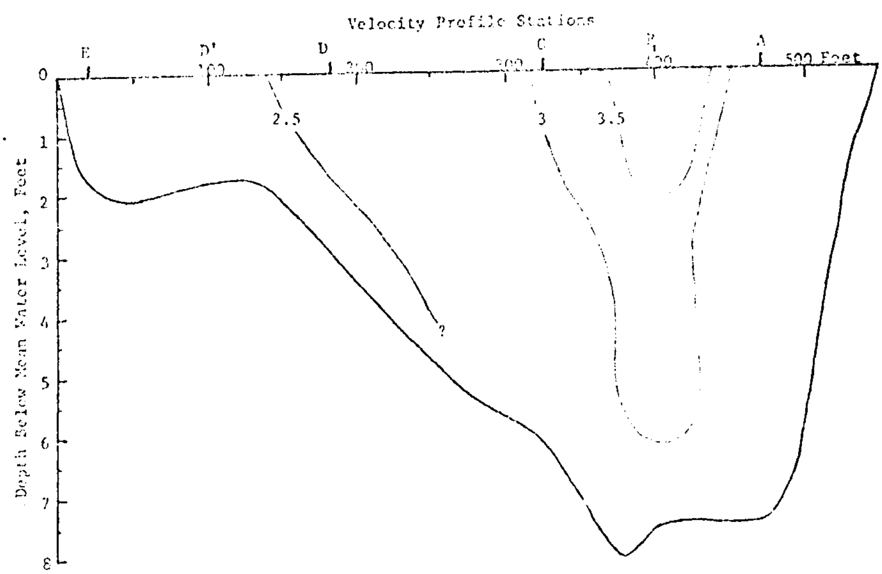



FIGURE 68.--CROSS-CHANNEL FLOOD VELOCITY DISTRIBUTION, 1530 5 MARCH, 1971

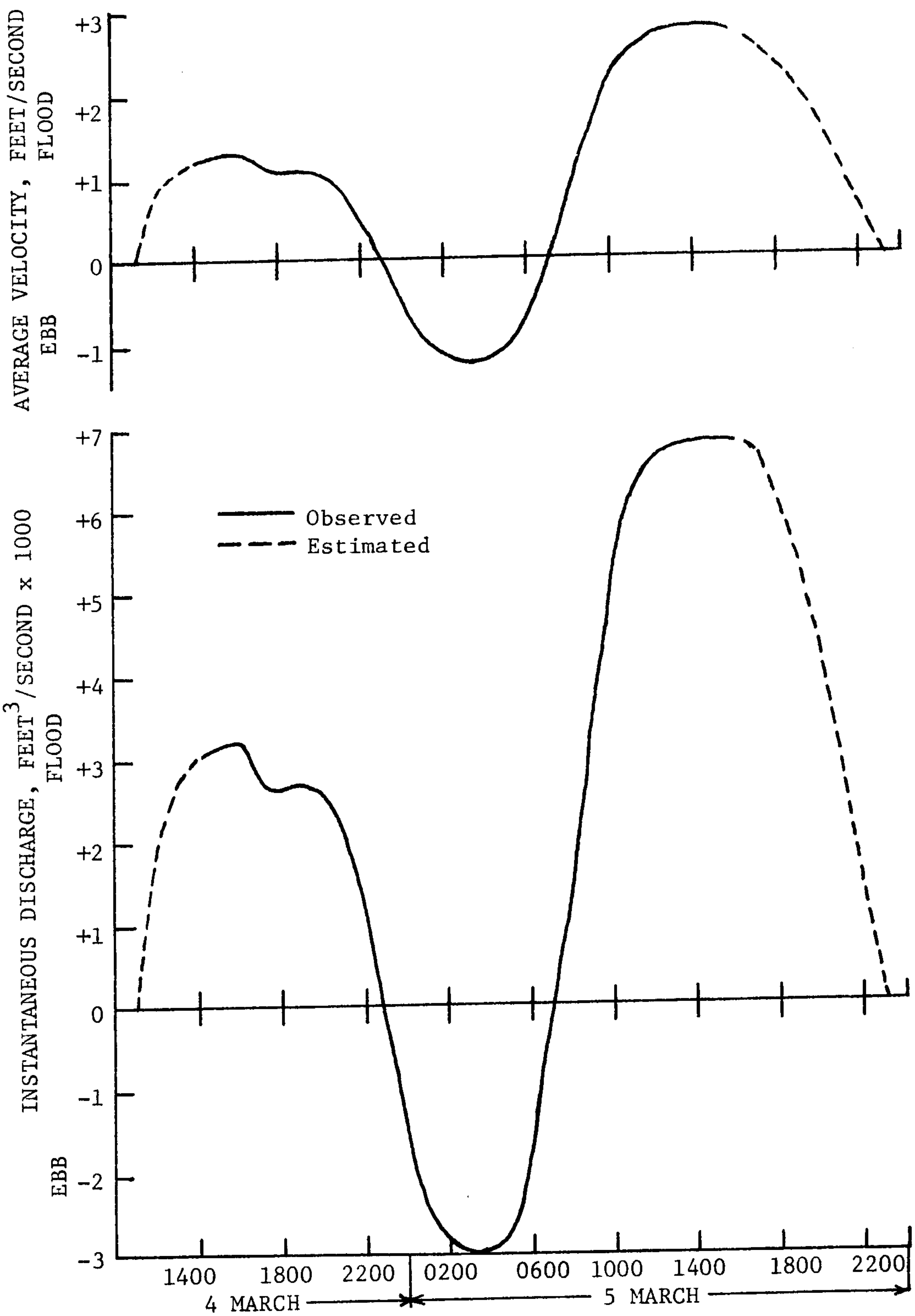



FIGURE 69.--INSTANTANEOUS AVERAGE VELOCITY AND DISCHARGE, 4 AND 5 MARCH, 1971

# APPENDIX.--TOPOGRAPHIC SURVEY DATA

This appendix presents results of field surveys conducted between October 24, 1970, and April 17, 1971 at Brown Cedar Cut. Permanent control markers are indicated in the figures by ⊕ symbols. Precise level methods established the elevation of the east marker to be 3.54 feet above local mean water level, and that of the west marker 4.11 feet. Contours of beach and shallow water areas were determined using transits, level rods, and plane-table plotting. Depths of the deeper channel areas and offshore gulf locations were established employing sonic measurement instruments. All contour values presented in the following figures are referenced to mean water level datum.

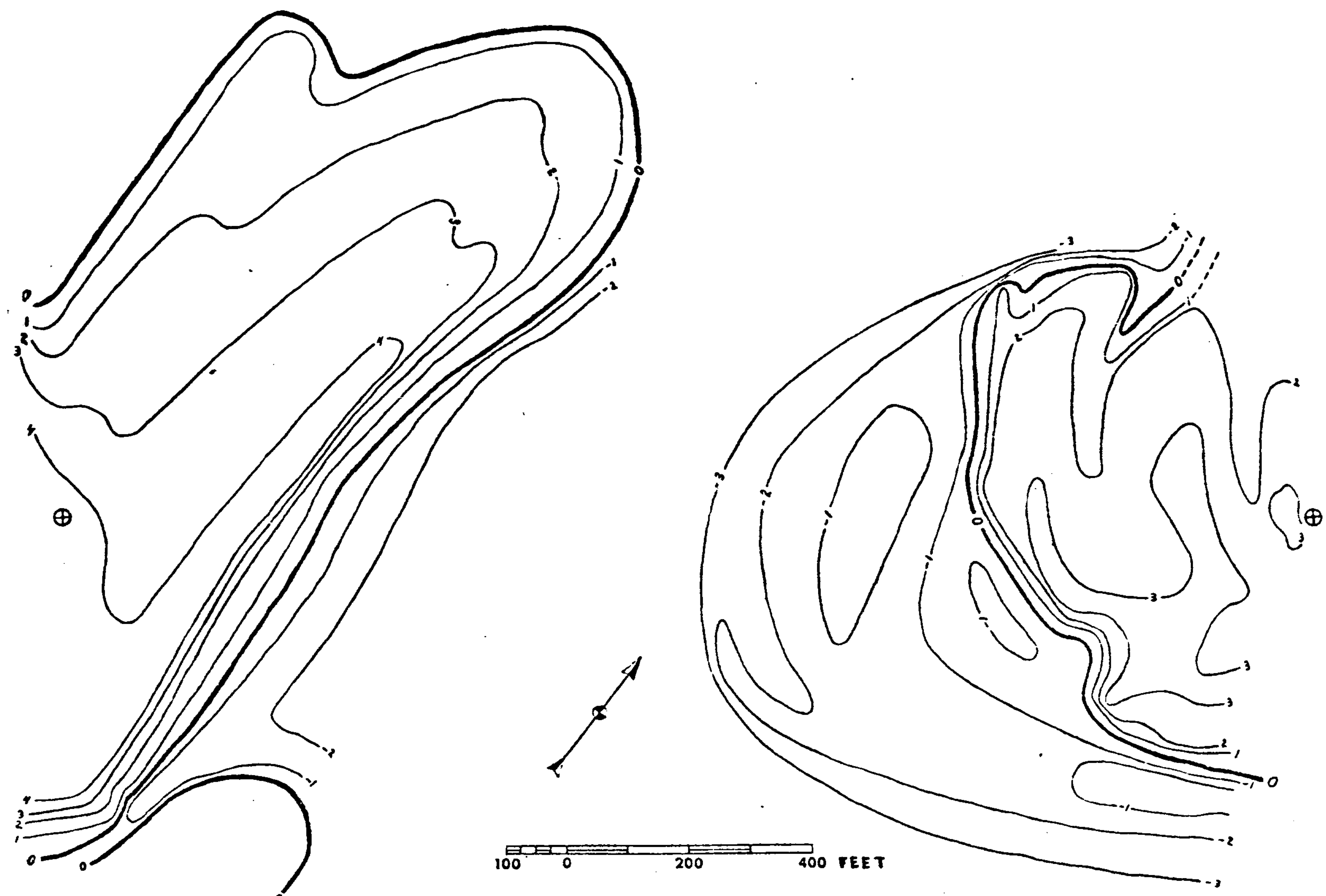



FIGURE 70.--BROWN CEDAR CUT TOPOGRAPHY, 24 OCTOBER, 1970

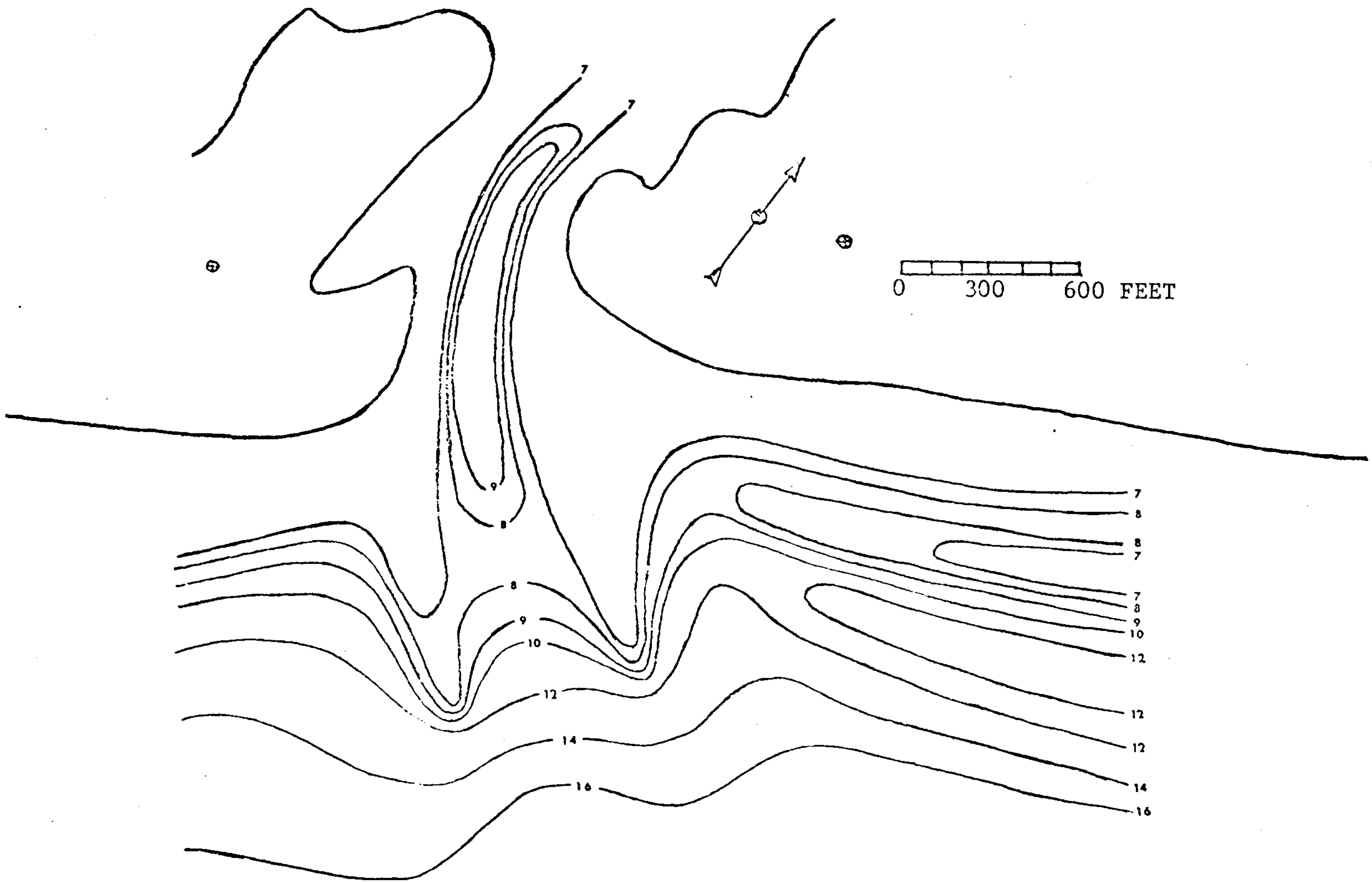



FIGURE 71.--OFFSHORE BATHYMETRY, 13 FEBRUARY, 1971

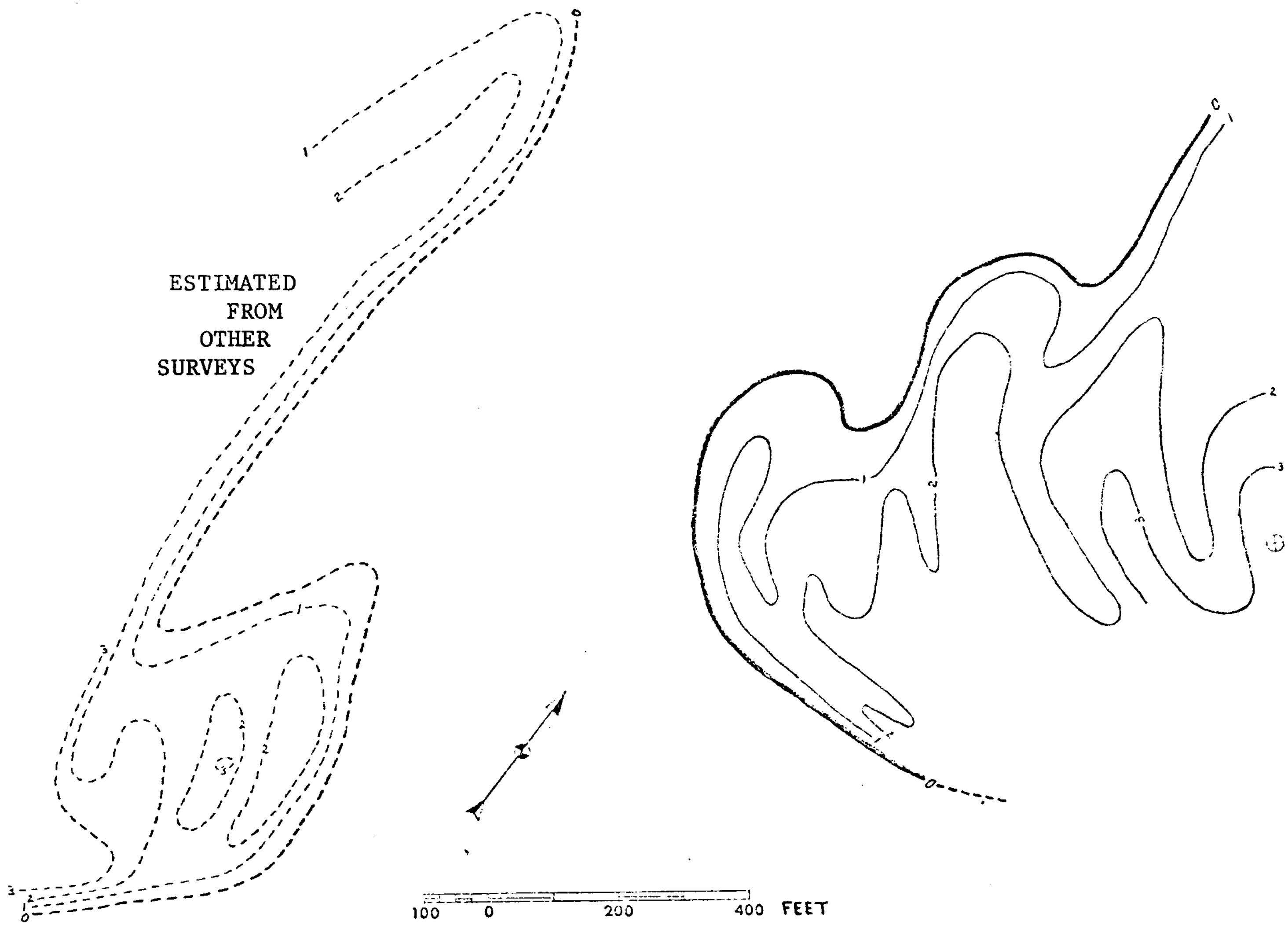



FIGURE 72.--BROWN CEDAR CUT TOPOGRAPHY, 20 FEBRUARY, 1971

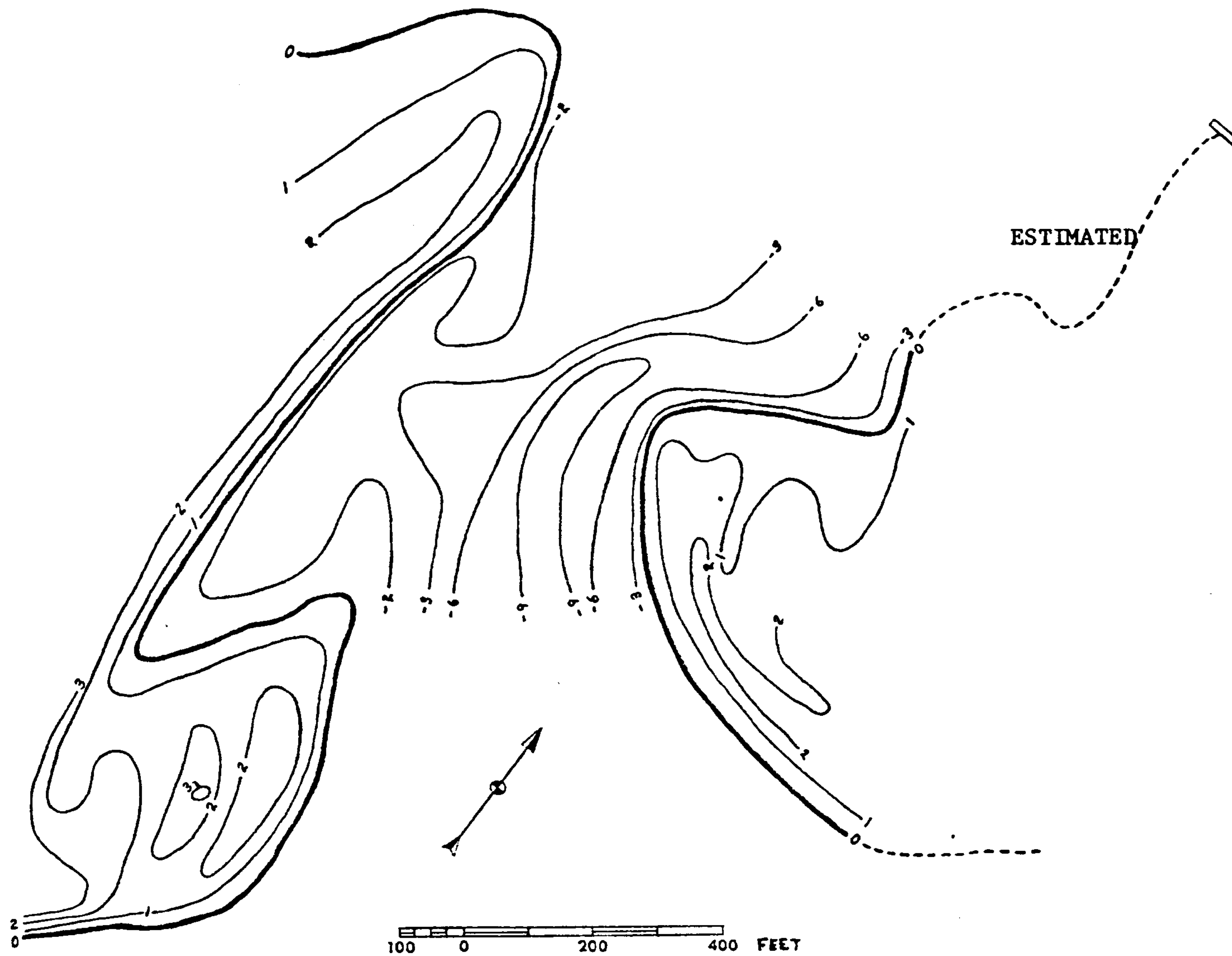



FIGURE 73.--BROWN CEDAR CUT TOPOGRAPHY, 27 FEBRUARY, 1971

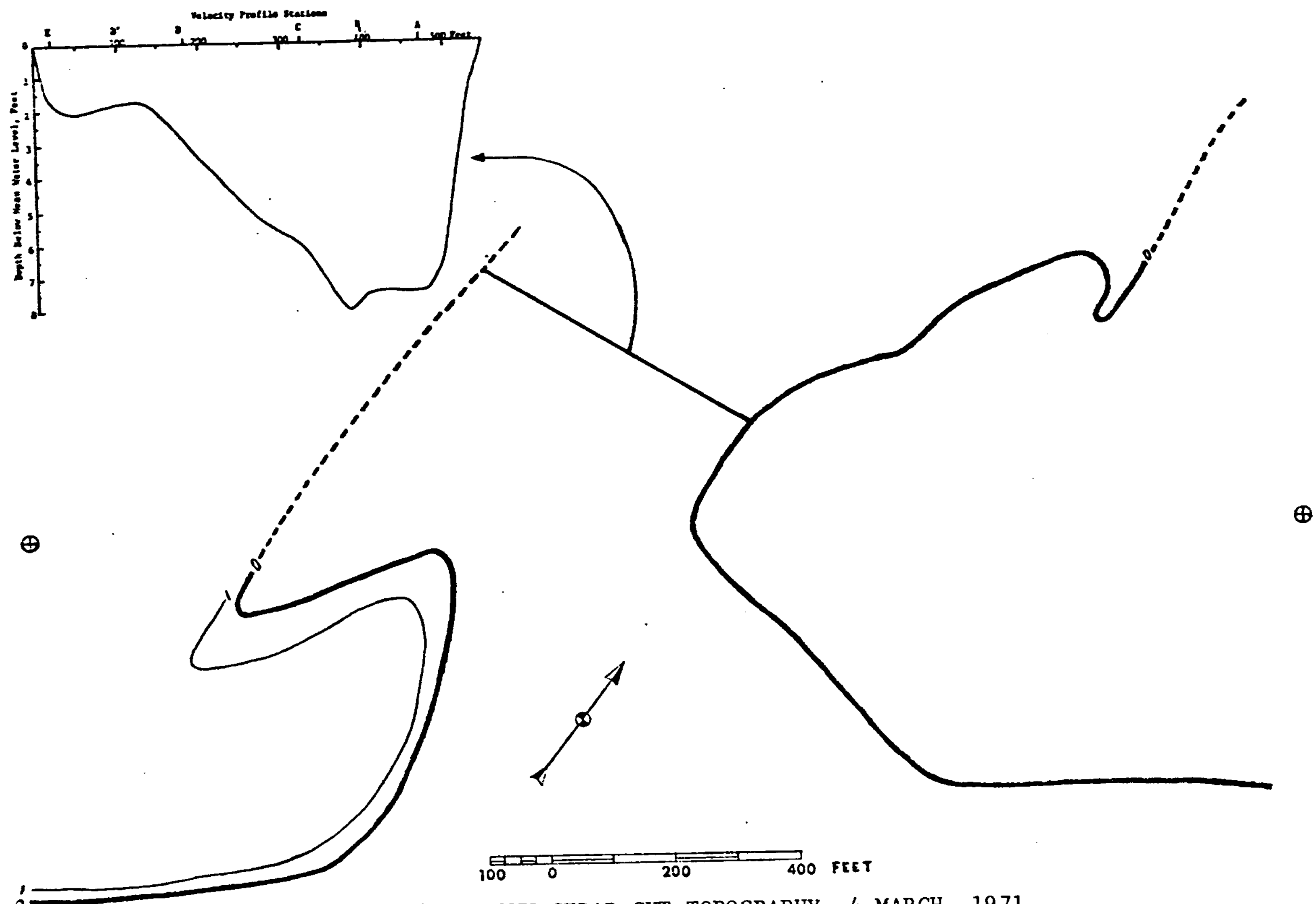



FIGURE 74.--BROWN CEDAR CUT TOPOGRAPHY, 4 MARCH, 1971

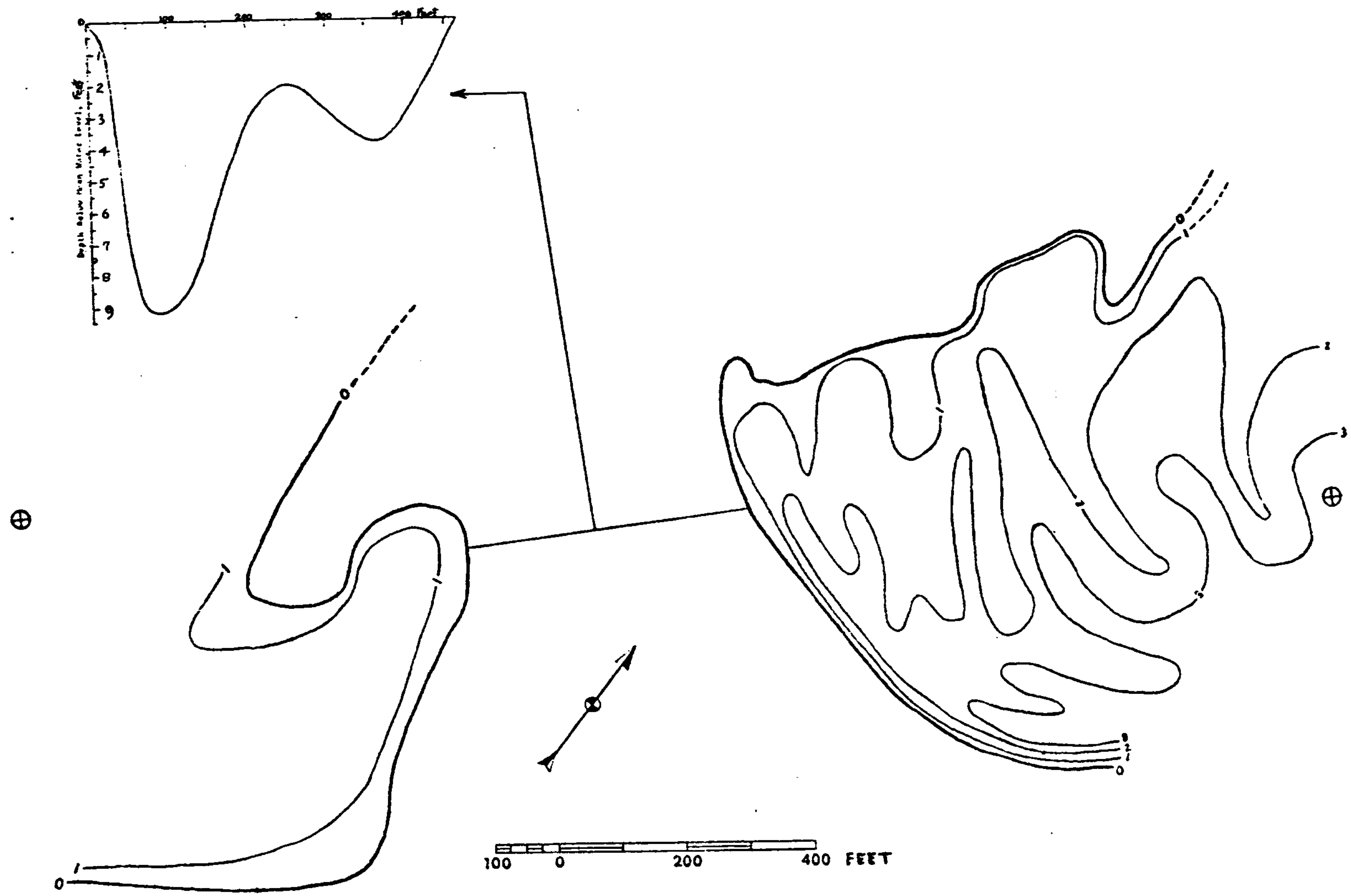



FIGURE 75.--BROWN CEDAR CUT TOPOGRAPHY, 20 MARCH, 1971

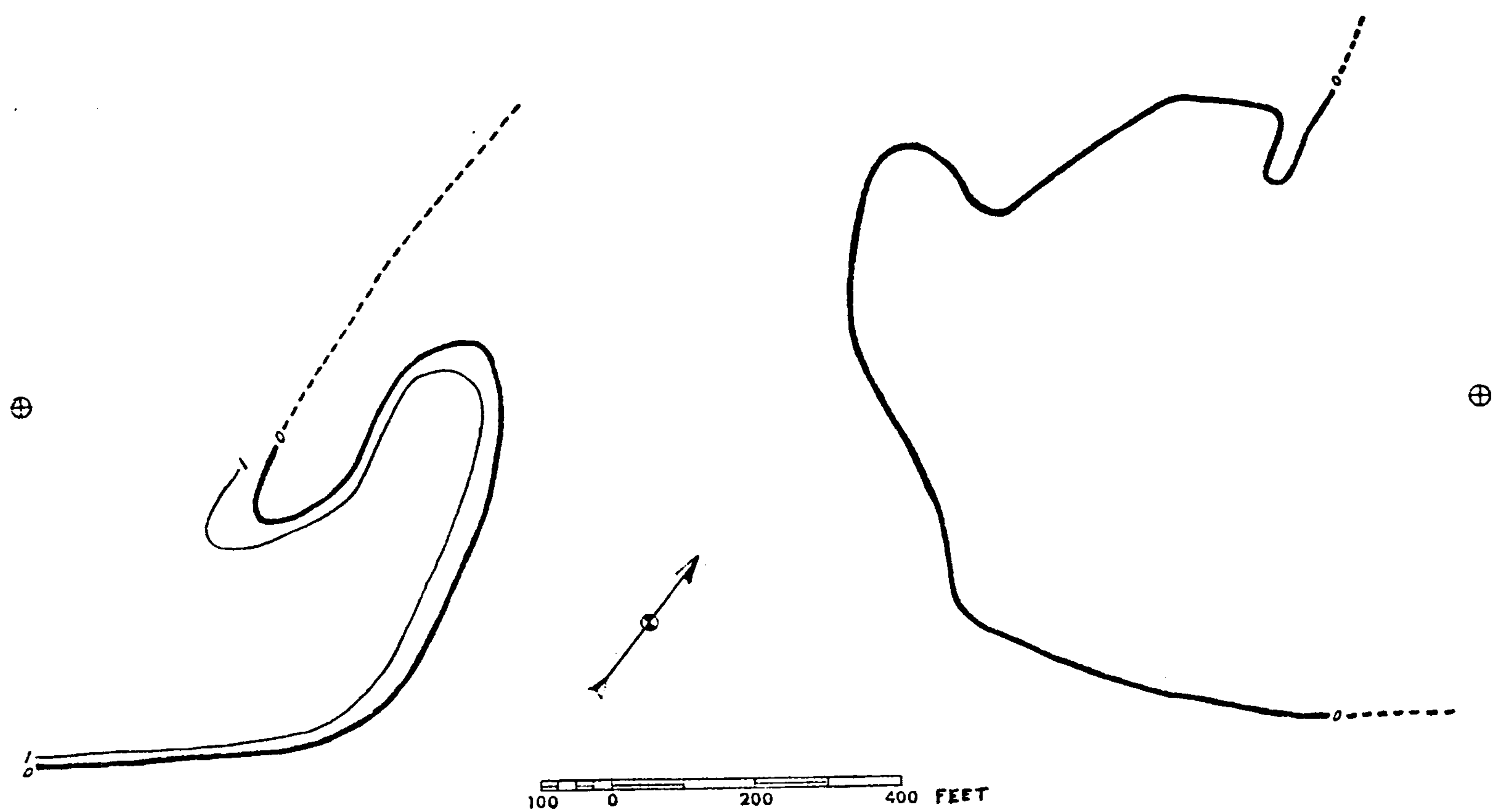



FIGURE 76.--BROWN CEDAR CUT TOPOGRAPHY, 3 APRIL, 1971

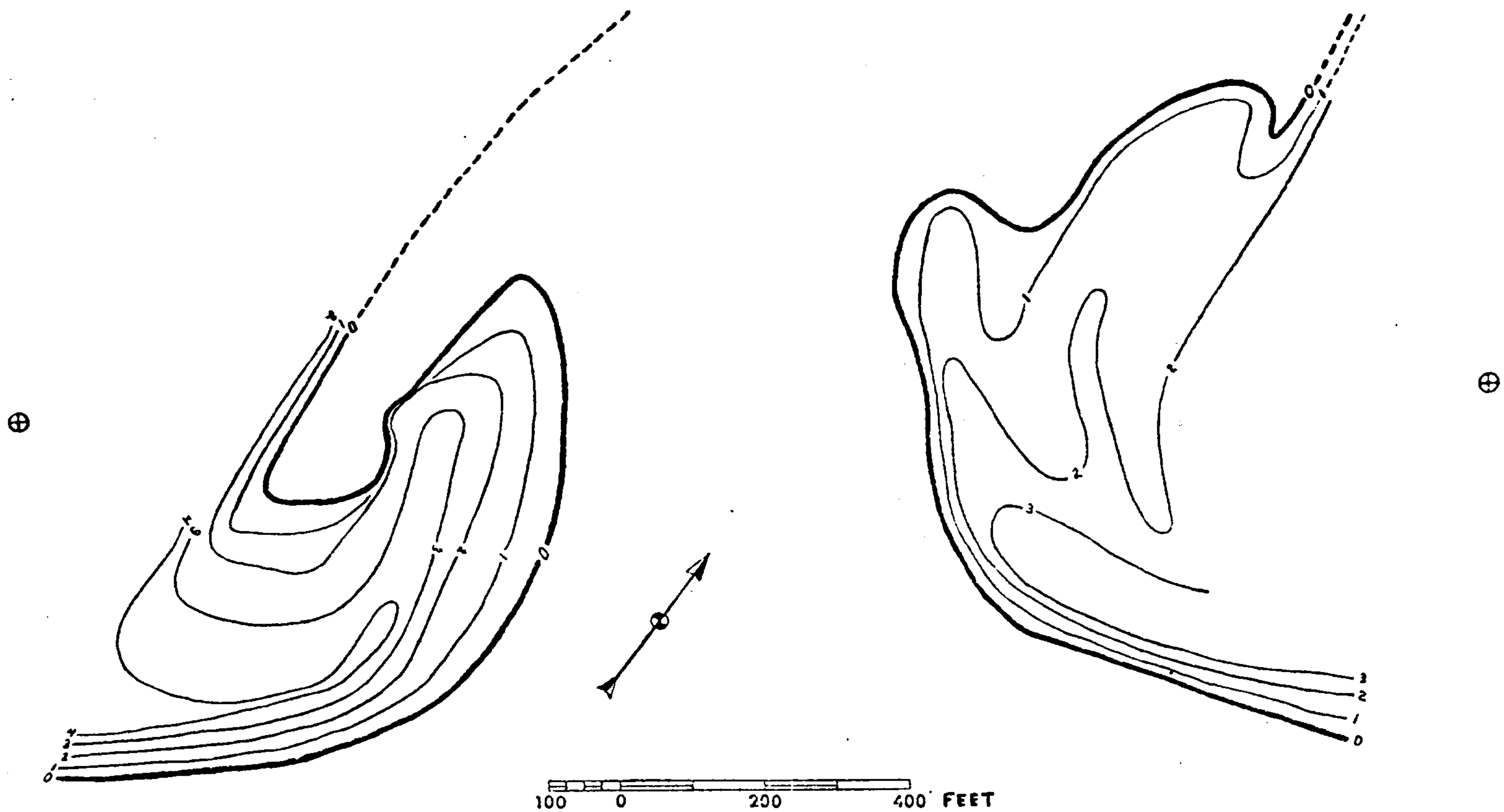



FIGURE 77.--BROWN CEDAR CUT TOPOGRAPHY, 17 APRIL, 1971